PRINCIPLES OF GUIDED MISSILES AND NUCLEAR WEAPONS

Prepared by

BUREAU OF NAVAL PERSONNEL

NAVPERS 10784

1959

PRINCIPLES OF GUIDED MISSILES AND NUCLEAR WEAPONS

Prepared and produced by the
U. S. Navy Training Publications Center
under direction of
the Bureau of Naval Personnel

NAVPERS 10784 1959

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C. - Price $2

THE UNITED STATES NAVY

GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

CONTENTS
Part 1. Guided Missiles

Part 2. Nuclear Weapons

Chapter 12—Fundamentals of nuclear physics

Chapter 13—Principles of nuclear weapons

Chapter 14—Effects of nuclear weapons

Appendix A

Appendix B

PREFACE

This is the second volume of a three-volume series of texts dealing with Naval weapons. The series is intended for use in the Naval Science curriculum of NROTC universities, and in other Navy training programs.

The first volume, *Principles of Naval Ordnance and Gunnery,* NavPers 10783, deals with conventional Naval weapons, and with the principles of fire control.

The present volume describes the principles of guided missiles and nuclear weapons, insofar as they can be discussed in an unclassified text. The treatment is necessarily of a general nature, with minimum reference to actual weapons in current use.

The third volume, a classified supplement to this text, will describe specific Navy missiles and nuclear weapons.

Part 1

GUIDED MISSILES

CHAPTER 1
INTRODUCTION TO GUIDED MISSILES

A. General

lA1. Definition

A GUIDED MISSILE is an unmanned vehicle hat travels above the earth's surface; it car-'ies an explosive war head or other useful payload; and it contains within itself some neans for controlling its own trajectory or light path. A glide bomb is propelled only by gravity. But it contains a device for control-ing its flight path, and is therefore a guided nissile.

The Navy's guided missiles, including Terrier, Talos, Sidewinder, Sparrow, Regulus, and Polaris, meet all the requirements of the above definition.

The Army's Honest John is a 3-ton rocket hat is capable of carrying a nuclear warhead. But because it contains no guidance system, Honest John is not a guided missile. The Navy's homing torpedoes are self-propelled weapons with elaborate guidance systems. The homing torpedo can hunt for a target and, when it finds one, steer toward it on a collision course. But because it does not travel above he earth's surface, the homing torpedo is not a guided missile.

A MISSILE is any object that can be pro-ected or thrown at a target. This definition ncludes stones and arrows as well as gun projectiles, bombs, torpedoes, and rockets. But in current military usage, the word MIS-SILE is gradually becoming synonymous with GUIDED MISSILE. It will be so used in this ext; we will use the terms MISSILE and GUIDED MISSILE interchangeably.

A2. Scope of the text

Part 1 of this book is a brief introduction o the basic principles that govern the design, onstruction, and use of guided missiles. Many f the principles we will discuss apply to all nissiles; most of them apply to more than one. The treatment will necessarily be general. ecurity requirements prevent any detailed escription of specific missiles in an unclassi-ied text. This text will therefore contain very ttle information about specific missiles; they will be described in some detail in a supplementary volume.

The reader will find some repetition in this text; this is intentional. The subject is complex; it deals with many different phases of science and technology. The beginning student of guided missiles faces a paradox. We might say that you can't thoroughly understand any part of a guided missile unless you understand all the other parts first. We will deal with this problem by first discussing the guided missile as a whole, with a brief consideration of its propulsion, control, guidance, and launching systems. Each of these subjects will then be treated at some length in one or more later chapters.

All guided missiles contain electronic devices; some of these devices are very complex. A sound understanding of the operating principles of missile guidance is impossible without some background in basic electricity and electronics. Appendix A of this text covers these subjects briefly. It may be used for a quick review. Students who have no background in electronics should use appendix A as an introduction to the subject; it should, if possible, be supplemented by further reading in basic texts on electricity and electronics.

1A3. Purposes and uses of guided missiles

As you well know, the primary mission of our Navy is control of the seas. We propose to keep the sea lanes open for our own and for friendly commerce; in time of war, we propose to deny use of the sea to our enemy. Historically, this mission has been accomplished by the use of warships armed with the most advanced weapons of their time. When John Paul Jones challenged the British control of the seas, his warships carried guns having an effective range of a few hundred yards. The Union Navy maintained a successful blockade of southern ports with the help of guns that could shoot a little more than a mile. The battleships of World War I carried rifled guns with an effective range in the order of 20 miles. When aircraft became more effective

weapons than guns, in both range and striking power, aircraft became the primary weapon of the Navy. The battle of the Coral Sea, in 1942, was the first major naval engagement in which surface ships did not exchange a single shot.

When a navy so controls the seas that it can safely approach the enemy coast, it can extend its striking power inland to the distance its weapons can reach. A battleship can bombard enemy installations more than 20 miles inland. Carrier-based aircraft extend the Navy's force for hundreds of miles over enemy territory. Thus, during the Korean War, the whole of North Korea was subject to attack by carrier-based aircraft of the U. S. Navy. The Navy's Regulus guided missile has a range comparable to that of carrier-based aircraft. And because it can be launched from submarines, Regulus can be used effectively even where we do not control the surface of the sea. The Polaris missile, also submarine-launched, will extend the Navy's striking power to 1,500 miles inland. And only a relatively small part of the earth's land surface lies more than 1,500 miles from the sea.

One of the strongest elements in our national defense is the Strategic Air Command, which can launch a devastating nuclear attack against any enemy on a few minutes notice. But SAC bases are large, and expensive to build and maintain. Their position is known to our possible enemies. At the outbreak of war, they would probably be the first objective in a surprise attack.

The intercontinental ballistic missile (ICBM) will carry a nuclear or thermonuclear warhead. It will reach its target, on another continent, within minutes after launching. It will approach the target at such a speed that any countermeasures may be very difficult. Its launching sites will be small, relatively cheap to build and maintain, and relatively easy to conceal. Because they can be widely dispersed, they will be difficult to attack even if their location is known. And the ICBM will not face the problem of returning safely to friendly territory after completing its mission, for guided missiles are expendable by design, while our strategic bombers and their crews are not. It is likely that SAC will first be supplemented, then replaced, by the ICBM.

The Navy's Polaris is an intermediate-range ballistic missile (IRBM). Polaris is another important element in our national defense planning. It will be armed with a nuclear or thermonuclear warhead. While SAC bases and ICBM launching sites are fixed in position, and therefore subject to attack, Polaris will be launched from submerged submarines, whose location the enemy cannot know or predict. The nuclear-powered missile-launching submarine may well be the capital ship of the future.

Modern military aircraft can fly so high and so fast that conventional antiaircraft guns are ineffectual against them. As you know, a gun is not aimed directly at a moving target; it must be so aimed that both the projectile and the target will reach a predicted point at the same time. During the flight time of the projectile, a high-speed high-altitude aircraft will travel several miles. Any slight change of course during that time will take it beyond the lethal range of the projectile burst.

The surface-to-air guided missile is a more effective means of defense against enemy aircraft. The missile can intercept attacking aircraft at greater heights, and greater ranges, than any projectile. And the aircraft is unlikely to escape a missile by taking evasive action. The missile is faster and more maneuverable. If the attacking aircraft changes its course, the missile guidance system will change the course of the missile accordingly, up to the instant of interception.

Guided missiles are becoming increasingly important in aircraft armament. When two jet aircraft are approaching each other head-on, the range closes at a speed between half a mile and one mile per second. Under these conditions it is difficult even to see an enemy aircraft, and hitting it with conventional aircraft weapons would be largely a matter of luck. But the air-to-air missile can "lock on" the hostile aircraft while it is still miles away, and it can pursue and hit the target in spite of its evasive maneuvers.

In the future, the defense of a naval task force against air attack will be somewhat similar to that of an American city or industrial area. The enemy attack will be detected by long-range search radar while the attacking planes are hundreds of miles from the target. Ashore, the early warning radars are located at distant outposts in Canada. At sea, they will be aboard picket vessels at some distance from the main body of the task force. The

first line of defense will probably be interceptor aircraft, which will attack the enemy planes with air-to-air missiles. A second line of defense may consist of moderate range surface-to-air missiles, which will intercept the attacking planes at ranges from about 30 to more than 100 miles. A third line would consist of shorter range missiles, designed to intercept at ranges between about 5 and 20 or 30 miles. Against enemy aircraft that penetrate these three lines of defense, conventional antiaircraft guns will be a last resort.

Because the defense system outlined above is formidable, it is improbable that enemy aircraft will try to bomb our cities, or attack a task force with bombs or torpedoes. Enemy aircraft are more likely to attack with air-to-surface missiles, launched at a range of perhaps a hundred miles.

One question remains: how are we to defend ourselves against enemy intercontinental ballistic missiles, and air-to-ground missiles? Our present surface-to-air missiles such as Nike and Terrier were designed for defense against jet aircraft. But Nike and Terrier are not fast enough for reliable defense against enemy missiles, which will approach at several times the speed of sound. The answer is an anti-missile missile, which will be relatively small, capable of launching on very short notice, extremely fast, and extremely maneuverable. Such missiles are now being developed.

When the anti-missile missile becomes operational it will probably lead to further developments. Our aircraft carry air-to-air missiles for defense against enemy aircraft; an intercontinental ballistic missile might carry air-to-air missiles for defense against other missiles. These might be called anti-anti-missile missile missiles, though if we have the ingenuity to develop such weapons we may be able to think of a shorter name for them.

Such speculations about the future are not very instructive. But this prediction is safe: the effort to develop faster and better missiles, and the race between missiles and missile countermeasures, will continue as long as the threat of war exists, or until some new and unforeseen weapon makes guided missiles obsolete.

1A4. Introduction to missile types

To perform the various functions outlined above, missiles of many different types must be developed. A list, later in this chapter, will show the number of missile types now operational or in various stages of development. It can be assumed that other missiles, not yet announced, are being developed.

The Navy's Sidewinder is a relatively small air-to-air missile with a range of a few miles. A Sidewinder costs about as much as a good used car. It resembles an ordinary aircraft rocket; it differs, of course, in having a guidance system, and movable control surfaces by which the guidance system can control its flight path. At the other extreme, the ICBM has a range of thousands of miles, with size and weight in proportion; its proportional cost is even higher. The ICBM, like most missiles, has the familiar rocket shape. But the Air Force Snark and the Navy's Regulus I, among others, resemble conventional aircraft; they differ in having a guidance system rather than a pilot, and they are designed to dive into their targets rather than release a bomb load and return.

Guided missiles are classified in a number of different ways; perhaps most often by function, such as air-to-air, surface-to-air, or air-to-surface. A nonballistic missile is propelled during all or the major part of its flight time; the propulsion system of a ballistic missile operates for a relatively short time at the beginning of flight; thereafter, the missile follows a free ballistic trajectory like a bullet (except that this trajectory may be subject to correction, if necessary, by the guidance system). Some missiles are designed to travel beyond the earth's atmosphere, and re-enter as they near the target. Others depend on the presence of air for proper operation of the control surfaces, the propulsion system, or both.

Missiles may be further classified by type of propulsion system, such as turbo-jet, ram-jet, or rocket; or by type of guidance, such as command, beam-riding, or homing.

1A5. Introduction to missile guidance

The missile guidance system keeps the missile on the course that will cause it to intercept the target. It does this in spite of

initial launching errors, in spite of wind or other forces acting on the missile, and in spite of any evasive actions that the target may take. The guidance system may be provided with certain information about the target before launching. During flight it may receive additional information, either by radio from the launching site or other control point, or from the target itself. On the basis of this information, the guidance system will calculate the course required to intercept the target, and it will order the missile control system to bring the missile onto that course.

From the paragraph above, it might be inferred that the guidance system is an intelligent mechanism that can think. This, of course, is untrue. The missile guidance system is based on a relatively simple electronic computer. But even the most complex computers, such as Univac and other "giant brains," can not think. Thinking is a conscious process, confined to man and a few of the higher animals. No matter how complex it may be, a computer is simply a machine built so that when certain things happen, certain other things will result. The design of a computer is nothing more than an advanced exercise in the logic of cause and effect. A computer can take no action that isn't built into it by its designer (except, of course, the erratic action that might result from a bad connection or a faulty component).

But in the later chapters of this text you will find many statements such as this: "When Terrier detects an AM signal, it knows it is off the beam center; but it does not know, from the AM signal, which way to go to get back to beam center." We will make such statements without further apology. But it is essential that the students understand what we are doing. We are using a convention, because it saves time and space. Remember that a missile doesn't "know," or "see," or "think," or "decide."

Several distinct types of guidance are possible; a given missile may use one type, or a combination of two or more. Although it can not be called a guided missile, the air-steam torpedo has a simple guidance system. Before launching, its gyro is set for a predetermined course; the gyro holds the torpedo on that course throughout its run to the target. The torpedo is capable of steering itself, but it receives no information after the instant of launching. This is PRESET guidance. The German V-1 is another example. Before launching, it was set to follow a given course, and to dive on its target after traveling a preset distance.

The German V-2 used a combination of preset and COMMAND guidance. Before launching, it was set to climb vertically for a certain distance, and then turn onto the desired course. Speed and position of the V-2 were determined by a radar at the launching site. This information was analyzed by a computer, which determined when the missile had reached a position and speed that would carry it, along a ballistic trajectory, to its target. At that instant, the missile propulsion system was shut down by radio command.

The Army's Nike surface-to-air missile is a more modern example of command guidance. Throughout the missile flight, radars at the launching site track both the missile and its target. A computer continuously calculates the course that the missile must follow to reach the point of intercept. Throughout its flight, Nike is steered along the desired course by radio commands from the ground.

Sidewinder has a HOMING guidance system. Sidewinder is sensitive to infrared (heat) radiation, and will steer itself toward any strong source of infrared. The exhaust of a jet aircraft is such a source, and Sidewinder can steer itself "right up the tailpipe" of an enemy jet.

Infrared is not the only basis for homing guidance. A missile can be designed to home on light, radio, or radar energy given off by, or reflected from, the target. (It could also, like a homing torpedo, be designed to home on a source of sound waves; but because a guided missile travels at from one to a dozen times the speed of sound, such a system would not be practical.)

Because its source of information is energy given off by the target itself, Sidewinder guidance is an example of PASSIVE homing. Other missiles carry a radar transmitter, "illuminate" the target with a radar beam, and home on the radar energy reflected from the target. This is an ACTIVE homing guidance system. A SEMI-ACTIVE system is also possible; the target is illuminated by a radar beam from the launching site or other control point, and the missile homes on energy reflected from the target.

The Navy's Terrier is similar to Nike in both function and performance; but its guidance system is entirely different. Terrier uses BEAM-RIDER guidance. A radar transmitter at the launching site keeps a narrow beam of radar energy continuously trained on the target. Terrier simply rides up the beam.

Intermediate-range (around 1,500 miles) and long-range (3,000 miles or more) missiles may use a NAVIGATIONAL guidance system. The missile determines its own position in relation to the target, calculates the course required to reach the target position, and steers itself along that course. A missile may be designed to navigate with the help of radio or radar beacons, just as a ship may navigate with the help of Loran. A missile may navigate by dead reckoning, through the use of an INERTIAL guidance system. It may navigate by taking star fixes through a telescope, or by examining the ground with radar and comparing what it sees with a map. Or it may use a combination of two or more of these methods.

As previously stated, a missile may have more than one type of guidance system, and switch from one to another during its flight. For example, a long-range missile may climb to a preset height and turn onto a preset course shortly after launching, then navigate to the target vicinity, and finally home on the infrared or other energy given off by the target. Or a surface-to-air missile may ride a radar beam until it gets near the target, then switch over to active homing guidance.

B. History of Guided Missiles

1B1. Introduction

The brief sketch that follows will enable the student to view the present-day guided missile in a historical perspective, and to consider the most recent developments in their relation to early experiments. It serves no other purpose; it is not necessary to memorize the dates listed here.

Guided missiles, as defined at the beginning of this chapter, were first used in World War II. But they could not have been built at that time without previous experiments in both propulsion systems and guidance. We will look briefly at early developments in both of those fields. Our latest missiles, of course, are based also on developments in many other fields, including mass production techniques, metallurgy, aerodynamics, radar, and electronic computers; but we cannot describe the evolution of those developments here.

1B2. Propulsion systems

Glide bombs and other gravity-powered missiles are obsolete. And although propeller-driven aircraft, under radio control, have been used as target drones, a propeller-driven guided missile would be too slow to be effective. All current missiles depend on some form of jet or rocket propulsion.

In France, in 1909, Guillaume outlined the basic theory of turbo-jet propulsion. In 1927, the Italian Air Ministry built and tested a plane driven by a form of mechanical jet propulsion. The fuselage of this plane was shaped like a tube, with flaring ends. A conventional propeller was mounted in the throat of the tube, forming a "ducted propeller" installation. This craft had good maneuverability and good stability, but in other respects its performance was poor. In 1932 Campini, an Italian, designed and later flew the first plane powered by a thermal jet; it differed from modern jets in using a piston engine, rather than a turbine, as a compressor.

After Campini's successful flight, development of improved jet engines was undertaken in several countries. In England, in 1930, Frank Whittle patented a jet engine based on the principles used in modern jet aircraft. After combustion, the exhaust gases of the jet were used to spin a turbine; the turbine, in turn, drove the compressor. The first successful flight of a turbo-jet powered aircraft was made in England in May, 1941. In the U. S., development of jet engines was turned over to General Electric Company, because of its experience with turbine-driven superchargers. At present, nearly every manufacturer of aircraft engines is developing and building turbo-jet engines.

The pulse-jet engine uses the forward motion of the missile or aircraft, rather than a turbine, to compress the air and fuel vapor before combustion. The pulse-jet principle was patented by a German engineer in 1930, and further developed by Bleeker, an American, in 1933. The pulse-jet engine was much improved by the Germans during World War II, and was used to power their V-1 guided missile.

The ram-jet also depends on forward motion for compression, but it differs from the pulse-jet in having no moving parts. The basic idea of a ram-jet was patented by Rene Lorin, a French engineer, in 1913. This was followed by a Hungarian patent in 1928, and another French patent, by Leduc, in 1933. None of these patents resulted in a workable ram-jet engine. The basic ideas were sound; but successful development of a ram-jet engine had to wait for extensive data on the behavior of fluids at extremely high speeds. In June of 1945, the Applied Physics Laboratory of the Johns Hopkins University made the first successful ram-jet flight, in the course of developing a power plant for the Navy's Talos missile.

Turbo-jets, pulse-jets, and ram-jets all depend on the presence of air for the combustion of their fuel. Consequently, none of them can operate beyond the earth's atmosphere. Rockets, on the other hand, carry their own source of oxygen for combustion; and they operate even more efficiently in a vacuum than they do in air. Rocket-propelled vehicles are theoretically capable of flight to the moon and the planets.

The principle of rocket propulsion has been known for nearly 2,000 years. In the Far East, rockets were used in warfare as early as the 13th century. Several western armies used rocket projectiles in the early part of the 19th century, but not very effectively. They seem to have been of more value in frightening the enemy than in doing physical damage. The British used rockets in their attack on Washington in 1812; and in the Star Spangled Banner, Francis Scott Key referred to the "rocket's red glare" during the bombardment of Fort McHenry. (But some historians believe that the British were using rockets as signals, rather than weapons.) Military interest in rockets lapsed after the middle of the 19th century, because developments in gunnery made gun projectiles superior to rockets in range, and far superior in accuracy.

Among rocket engineers, Robert H. Goddard is known as the "Father of Rocketry." Goddard was born in Massachusetts in 1882. By the time he earned his Bachelor of Science degree in 1908, he was obsessed by thoughts of rockets and rocket propulsion. He believed, quite correctly, that rocket propulsion would be the most suitable means for sending measuring instruments to the top of the earth's atmosphere, and eventually to the moon. Up to that time no one had investigated the physics of rocket propulsion, and no one had worked out the necessary mathematics. Goddard decided to do both.

Before Goddard's experiments, rockets consisted of a quantity of propellant packed in a cylindrical tube. Goddard discovered that by forming the after end of the tube into a smooth, tapered nozzle, he could increase the ejection velocity of the combustion gases eight times, without increasing the weight of the fuel. According to Goddard's calculations this would, for a given weight of fuel, drive the rocket eight times as fast and sixty-four times as far.

Goddard was given a Navy commission in 1917, and assigned to the job of improving the Navy's signal rockets. This assignment enabled him to continue his development of rocket theory. After the war he summarized his theories and experience in a paper called *A Method of Reaching Extreme Altitudes*. This report was published by the Smithsonian Institution in 1920. It consisted almost entirely of equations, formulas, and tables, but it contained one statement of general interest. It proposed the idea of multi-stage or step rockets—that is, one rocket carrying another—and said that by this means a rocket could be sent to the moon, where it could explode a charge of flash powder to make a light visible from the earth.

During the twenties and early thirties, Goddard continued his experiments with the help of a small salary (as professor of physics at Clark University) and grants from the Guggenheim and Carnegie Foundations. His list of accomplishments is impressive. We have mentioned his idea of multi-stage rockets, and his design of the tapered nozzle. He was the first to suggest that a liquid-fueled rocket could provide the sustained thrust necessary for sending a vehicle into space. He was the first to actually launch a successful

liquid-fueled rocket. (That was on 16 March, 1926; the rocket reached an altitude of 184 feet.) He proved, first by calculation and later by experiment, that rocket propulsion can be used in a vacuum. He was the first to fire a rocket that traveled faster than sound; he was the first to develop a gyroscopic steering mechanism for rockets; and he was the first to use vanes in the jet exhaust stream to stabilize the rocket during the first phase of its flight.

But Goddard was forced to end his experiments in 1935, for lack of funds. During World War II he again worked for the Navy, this time to develop rockets to aid the take-off of the Navy's flying boats. He died in 1945.

A group or rocket enthusiasts, inspired by Goddard's experiments, formed the American Rocket Society in 1930. During the thirties this group performed a number of important experiments with rocket motors, but their work was limited in scope by lack of money.

Hermann Oberth is a German counterpart of Goddard. Like Goddard, he worked on the physics and mathematics of rocket propulsion during the first World War. There is good evidence that he independently conceived the idea of multiple-stage liquid fuel rockets. He read Goddard's report shortly after it was published, and in 1923 published a book of his own, called *The Rocket into Interplanetary Space*. Goddard's principal interest was in scientific exploration of the upper atmosphere; but to Oberth, every improvement in rocketry was simply a step toward the eventual development of space ships. Oberth's book discussed the possibility of putting an artificial satellite into orbit around the earth. (Except for a science-fiction story published in 1870, that was the first time this idea had been expressed in print.) Oberth believed that passengers could travel to and from the satellite in smaller "landing rockets." In this way, the satellite could be transformed into a manned space station, which could ultimately serve as a launching point for space ships. Neither Goddard nor Oberth mentioned the possible use of rockets as military weapons.

The German "Society for Space Travel, Inc." was organized in 1927, with Oberth as president and Willy Ley as vice president. The society began at once to experiment with liquid-fueled rocket engines. The rockets carried two tanks—one of gasoline and one of liquid oxygen. These two liquids had to be fed simultaneously, and in the right proportions, to the combustion chamber, where they were mixed and burned. Most of the attempted launchings ended in failure, for one of two reasons. First, liquid oxygen is extremely cold; it froze the valves, so that they refused to open or close at the proper time. (There is still no completely reliable solution for this problem.) Second, the combustion temperature was so high that the rocket burned up after a few seconds. In later experiments, the combustion chamber was surrounded by a cooling jacket filled with water. With this model, the society launched a number of rockets that burned for about thirty seconds, and reached an altitude of half a mile or more. The next step was to omit the water from the cooling jacket, and circulate the fuel through the jacket before burning it. When the society tried to launch such a rocket, using gasoline as fuel, it immediately exploded. Ley suggested using ethyl alcohol, slightly diluted with water, in place of gasoline. This system worked very well. The same system, and the same fuel combination, were later used in the German V-2 missiles, the American Viking rockets, and the rocket-propelled experimental planes X-1 and X-1A.

The Versailles peace treaty limited the German army to 100,000 men; it was forbidden to have aircraft or antiaircraft guns, or field artillery of more than 3-inch caliber. This may explain why the German army took an early interest in rocket development; the treaty of Versailles didn't mention rockets at all. In 1932, the army established a small research project under the direction of Captain (later General) Walter Dornberger, to develop liquid-fueled rockets for use as weapons. No one in Germany had any experience with rocket propulsion, except the members of the Society for Space Travel. Dornberger visited the society, and hired a very young member named Wernher von Braun.

The team of Dornberger and von Braun, with a small staff of assistants, began to test rocket motors on an artillery testing range near Berlin. In December of 1934, they succeeded in firing two rockets to a height of about 6,500 feet. This news eventually filtered up to the high command. In 1936, General von Fritsch went to the test range for a demonstration. The general was impressed. The result

was a new and much bigger research institute—the Peenemunde Project.

1B3. Guidance systems

The history of guidance systems is short. All of the significant developments are recent, principally because the state of electronics before the nineteen forties was relatively primitive.

The Americans developed a flying bomb called the Bug during the first World War; it was simply a pilotless aircraft, with a range of about 400 miles. The Bug was ready for production by the middle of 1918. But by that time it was apparent that the war would be over in a few months, and the Bug was never produced. Its accuracy would have been poor; it had no guidance system. But the Bug led to the suggestion that pilotless aircraft could be controlled by radio. Beginning in 1924, both the Army and Navy experimented with radio-controlled planes. Several moderately successful flights were made, with the pilotless plane controlled by radio from a parent plane that flew nearby. This project was dropped in 1932 for lack of money.

In 1935, an American high-school student named Walter Good built and flew a radio-controlled model airplane. This was the first time on record that a plane of any kind had been successfully launched, flown, and landed while under complete radio control from the ground. One of the problems that plagued the armed forces was stabilization—keeping the aircraft on an even keel so that it could respond properly to radio commands. Because a well-built model airplane is inherently stable, Good didn't have to worry about this problem. His contribution was to design and build a miniature radio receiver coupled to the control surfaces through a miniature servo system.

The Army and Navy resumed their experiments with radio command during the late thirties, and by 1940 both had developed radio-controlled planes for use as target drones. As we will note below, missiles with elementary preset and command guidance were used during World War II. But successful beam-riding, radar and infrared homing, hyperbolic, and inertial guidance systems are all postwar developments.

It may be worth mentioning at this point that many of the pioneers in the fields of missile guidance and propulsion are still (in 1959) actively at work on guided missile development. Dr. Walter Good is working at the Applied Physics Laboratory of Johns Hopkins University, where he helped to develop the guidance system for the Navy's Terrier. Dornberger is head of the missile department of Bell Aircraft in Buffalo, N. Y. Wernher von Braun is chief of the U.S. Army's Ballistic Missile Agency in Huntsville, Alabama, and Oberth is one of his assistants. And Willy Ley is probably the world's most popular author on the subjects of rockets, missiles, and space travel.

1B4. Guided missiles in World War II

During World War II, the Japanese developed and used two devices of interest in the history of guided missiles. One of these was an air-launched, radio-controlled, rocket-assisted glide bomb. Its performance was limited. It had to be launched from a plane at low altitude, within two and a half miles of the target. This made the launching planes highly vulnerable to antiaircraft fire, especially after we began to use the proximity fuze. The Japanese dropped this project before the end of the war.

The second Japanese missile was the baka bomb. This was a rocket-propelled glide bomb designed for use against shipping. It carried a human suicide pilot; for this reason we can't call it a true guided missile. The baka bomb had poor maneuverability, and because of this we were able to shoot down a great many of them with antiaircraft fire.

Of the guided missiles used during World War II, those made by the Germans were the most advanced, and the most effective. The V-1 and V-2 are familiar to nearly everyone. The V-1 was developed early in the war, and was successfully flight-tested at Peenemunde as early as the spring of 1942. By 1943, the Peenemunde center was working on 48 different antiaircraft missiles. Because of this dilution of effort, progress was slow. The work was later consolidated into 12 projects in an effort to get the missiles into production in time to influence the outcome of the war.

The V-1 was a robot bomb—a pulse-jet midwing monoplane with a conventional airframe and tail construction. It used gyro

stabilization and preset compass guidance. It was launched from a ramp with the help of boosters, and had to reach a speed of about 200 mph before its engine developed enough thrust to keep it airborne. V-1 missiles were launched against England in large numbers, and their 1-ton warheads did enough damage to have a serious effect on morale. But the V-1 missiles were slow, and after proximity fuzes were rushed to England to combat them, about 95% of them were brought down by antiaircraft fire.

The V-2 was a large missile, with a length of 46 ft 11 in., and a diameter of 5 ft 5 in. Its total weight at launching was over 14 tons, including a 1650-pound warhead. The V-2 was propelled by liquid-fuel rockets. It was launched vertically, and preset to tilt over to a 41- to 47-degree angle a short time after launching. When it reached a speed calculated to take it to the target, its propulsion system was shut down by radio command, and it then traveled a ballistic trajectory. Its accuracy was not high, and its maximum range was only about 200 miles. But it descended almost vertically on its target, at speeds of from 1800 to about 3300 mph. Active countermeasures against it were impossible; no V-2 missile was ever intercepted, or shot down by antiaircraft fire. If armed with a nuclear warhead, the V-2, within the limits imposed by its range, would be a formidable weapon even now.

Five other German missiles, which were in various stages of final testing when the war ended, are worth a brief mention:

Rheinbote was a surface-to-surface missile propelled by a three-stage rocket, with booster-assisted take-off. Its overall length was 37 ft; length of the third stage was 13 ft. The third stage carried 88 pounds of explosive; it reached a speed of over 3200 mph about 25 seconds after launching, and had a range of about 135 miles.

Wasserfall was a supersonic surface-to-air missile, propelled by a liquid-fuel rocket and guided by radio command. Length: 25 ft; weight: 4 tons; speed: 560 mph; range: 30 miles; war head: 200 pounds.

Schmetterling was a smaller version of Wasserfall, intended for use against low-altitude targets at ranges up to 10 miles. It carried a 55-pound warhead.

Enzian was another surface-to-air missile, designed for use against large bomber formations. Its length was about 12 ft, and wingspan about 14 ft. It carried about 1000 pounds of explosive. It was propelled by a liquid-fuel rocket, and was launched with four solid-fuel booster rockets.

The X-4 was an air-to-air missile designed for launching from fighter aircraft as shown in figure 1B1. It was propelled by liquid-fuel rocket, and stabilized by four fins placed symmetrically. Length: about 6-1/2 ft; span about 2-1/2 ft; range 1-1/2 miles; speed 560 mph at an altitude of 21,000 ft. The X-4 was guided by commands from the launching aircraft, through a pair of fine wires that unrolled from two coils mounted on the tips of the missile fins. The X-4 was successfully tested before the end of the war, but it was not used in combat.

In the United States, the Army Air Corps began the development of guided glide bombs in 1941. Azon was a vertical bomb controlled in azimuth only; it was put into production in 1943. Razon, a bomb controlled in both azimuth and range, was started in 1942 but not completed until the end of the war. The limits of control of Azon and Razon bombs are indicated in figure 1B2. A medium-angle glide bomb called the ROC, and a 12,000-pound bomb called Tarzon, both controlled in azimuth and range, were developed during the war but were not used in combat. The Tarzon project was dropped in 1946 but resumed in 1948, and Tarzon was used successfully during the Korean war.

In 1944, we carried out a glide-bomb mission against Cologne, Germany, and a majority of the bombs reached the target area. In this same year remote television-control equipment was developed and installed in bombing aircraft. These aircraft were used to control television-sighted, explosive-laden bombers unfit for further service. These radio-controlled bombers saw some service over Germany in the "Weary Willie" project.

Our first jet-propelled missile was a radio-controlled flying wing; a later version was a copy of the German V-1, with a few improvements.

By the end of the war, the Navy had a number of guided missile projects in various

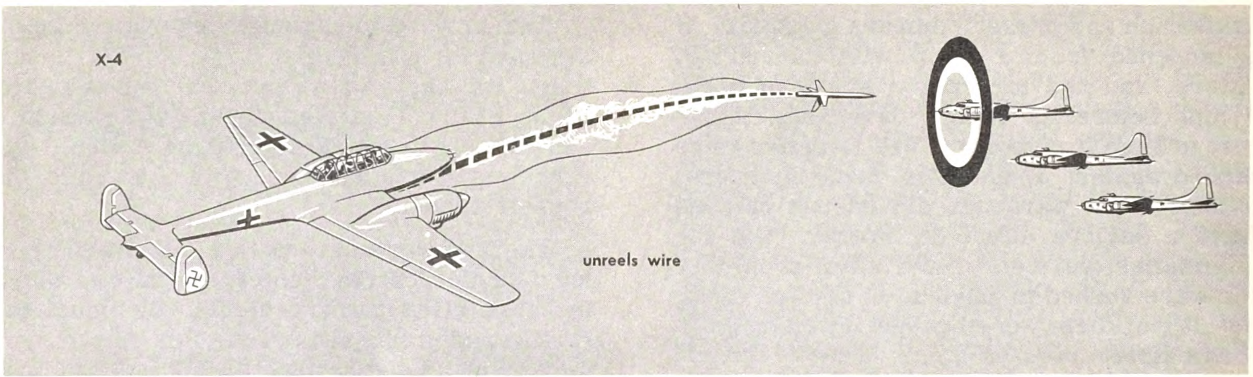

Figure 1B1.–Launching of an X-4.

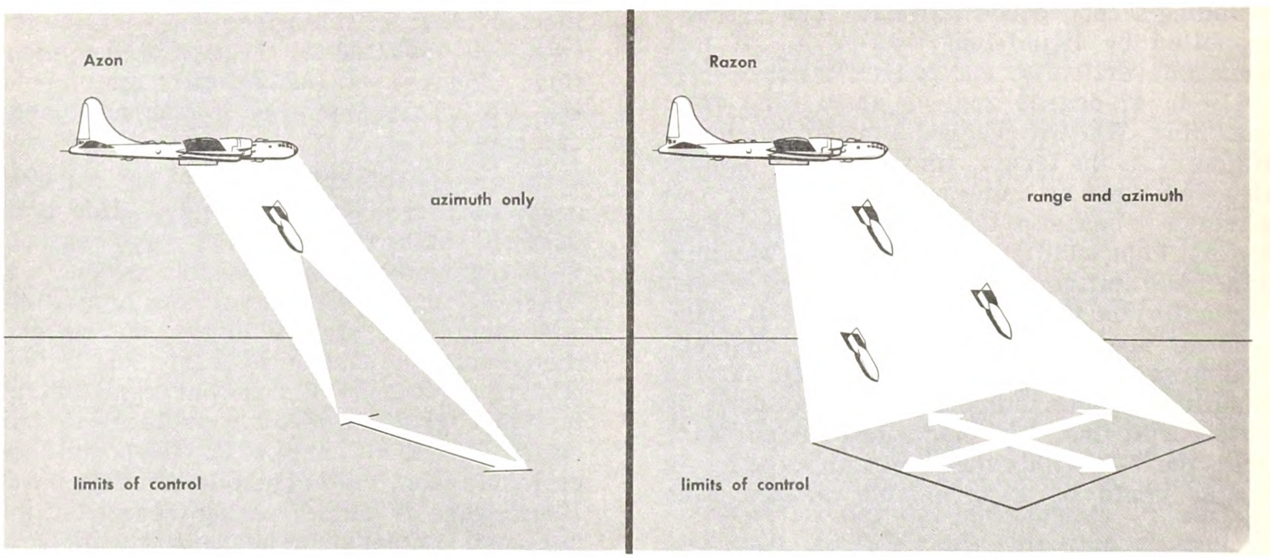

Figure 1B2.–Limits of control of the Azon and Razon.

stages of development. The Gargoyle was an air-launched, powered, radio-controlled glide bomb with a flare for visual tracking. Another Navy glide bomb, the Glomb, carried a television monitor through which the pilot of the launching aircraft could observe its approach to the target; it was guided by radio command. The Loon was a U. S. Navy version of the German V-1, intended for shore bombardment. The Gorgon IIC was propelled by a ram-jet engine, tracked by radar, and guided by radio command. In 1944, the Navy assigned development of the Bumblebee project to the Applied Physics Laboratory of the Johns Hopkins University. This project has produced Terrier, Talos, and Tartar, as well as the now discontinued Triton.

1B5. Missile developments after World War II

As we have shown, the principal guided missile developments during World War II were German. The United States lagged far behind. Japanese and British missile developments were insignificant, and as far as we know the Russians had none at all. In 1945, the Russians captured most of the production engineers and technicians of the V-2 project, as well as several tons of missile data and perhaps a few V-2 missiles. We were luckier than the Russians. The design staff of the Peenemunde project, including von Braun and his principal assistants, took pains to surrender to the Americans rather than to the

Russians. And we captured and shipped to the proving ground at White Sands, New Mexico, enough intact V-2's and spare parts to make, eventually, about 70 complete missiles.

During the first few years after the war, both American and Russian missile effort was partially devoted to assimilating the German developments. Our own experiments with the captured V-2's provided valuable training for launching crews, and valuable knowledge of missile engineering. Our "V-2 Program" ran from March 1946 to June 1951. One of its principal successes was a high-altitude record of 250 miles, achieved by a WAC-Corporal missile boosted by a V-2. This record stood for many years. (At the moment of writing, the high-altitude record is about 80,000 miles; we expect this figure to look small by the time you read this.)

Postwar missile development has been rapid. Many missiles are now operational; many others have been abandoned at various stages of development, or rendered obsolete by more advanced weapons. We will not try to cover these developments here; a list of obsolete missiles would probably be longer than a list of those now current.

C. Classification of American Guided Missiles

1C1. General

Although missiles are popularly known by their names, such as Sidewinder or Terrier, every missile is assigned a designation consisting of letters and numerals. The first three letters indicate the intended use of the missile:

AAM—air-to-air missile
ASM—air-to-surface
AUM—air-to-underwater
SAM—surface-to-air
SSM—surface-to-surface
UAM—underwater-to-air
USM—underwater-to-surface

These three letters are followed by a hyphen and then a service letter: A for Air Force, N for Navy, and G for Army. After another hyphen comes the model number, followed by a lowercase letter indicating successive modifications. A one-letter prefix may be used to indicate the status of the missile: X means experimental, Y means service test, and Z means obsolete. No prefix is used if the missile is operational. For example:

ASM-G-3c—An air-to-surface missile used by the Army; third model and third modification, operational.

XSAM-N-7—A surface-to-air missile used by the Navy, seventh model, experimental. (This designation was used for an early version of Terrier.)

All missiles in service, as well as most of those still under development, have been given popular names. Some of these names follow this pattern:

AAM—Winged creatures (except birds of prey and game birds). Example: Sparrow.
SAM—Mythological terms. Example: Talos.
SSM—Astronomical terms. Example: Polaris.

At the present time, most missiles appear to be exceptions to the above "rules." For example, Sidewinder and Bullpup are not winged creatures; Terrier is not a mythological term; Snark, Thor, Lacrosse, and Dart are not astronomical terms.

D. Current American Service Missiles

1D1. General

Because of the rapid developments in the guided missile field, the lists given below will be out of date before you can read them. Some of the missiles listed may have become obsolete. Others, now under development, will probably be announced.

1D2. Army missiles

Nike-Ajax SAM is the Army's first supersonic anti-aircraft guided missile. It is designed to intercept and destroy attacking enemy aircraft regardless of evasive action. Nike guided missile units are now deployed around vital industrial, highly populated, and strategic

areas of the United States. Nike-Ajax is about 20 ft long and 1 ft in diameter, with two sets of fins for guidance and steering. It is boosted to supersonic speed by a solid-propellant booster, and maintained by a liquid-fuel sustainer motor. The missile and booster together weigh more than a ton. There are 12 launchers in each Nike battery, which is operated by about 100 officers and men.

Corporal SSM may be equipped with either a nuclear or a conventional warhead. It can engage tactical targets at ranges of 75 miles or more. Corporal gives the Army field commander great firepower on the battlefield, and enables him to strike selected targets deep in enemy rear areas. Corporal follows a ballistic trajectory during most of its flight; weather and visibility conditions place no restriction on its use. The propulsion system uses a liquid-fuel rocket motor. The missile travels through space at several times the speed of sound. A Corporal battalion has 250 men. Each battalion has two batteries—a firing battery and a Headquarters Service battery. There are two operational launchers to a battalion. Corporal battalions are now deployed in Europe.

Sergeant SSM is a ballistic guided missile intended to replace Corporal, with improvements in power, range, and accuracy.

Redstone SSM is a supersonic ballistic missile with a range of several hundred miles, designed to extend and supplement the range and fire power of Army artillery.

Jupiter SSM is the Army's intermediate-range ballistic missile. Its range is in the order of 1,500 miles, and it is propelled by a liquid-fuel rocket.

Lacrosse SSM is used in close tactical support of ground troops. It is an all-weather missile, propelled by a solid-fuel rocket motor, and capable of carrying highly effective area-type warheads. It will supplement, and perhaps eventually replace, conventional artillery. The Lacrosse system includes the missile, a launcher mounted on a standard Army truck, and other ground equipment.

Dart SSM is a guided anti-tank missile, propelled by a solid-fuel rocket, and designed for use by front-line troops. It carries a warhead capable of defeating the heaviest known enemy armor, and delivers this warhead with pinpoint accuracy. The Dart can be launched by a lightweight launcher from a variety of vehicles.

Nike-Hercules SAM is capable of carrying a nuclear warhead; it is designed for use against either single aircraft or whole formations of aircraft. The missile is 27 ft long, the booster 14-1/2 ft long. Both use solid propellant. The warhead is provided with a safety feature, so that it can detonate only at altitudes sufficiently high to prevent damage to friendly surrounding terrain.

Hawk SAM is designed to supplement the Nike missile system by destroying attacking aircraft at low altitudes. The launching facilities are sufficiently portable to be used by fast-moving combat troops. Hawk is propelled by a solid-fuel rocket. The missile is about 17 ft long, and about 14 in. in diameter.

Nike-Zeus SAM is an anti-missile missile equipped with a nuclear warhead, and designed to defend the United States against attack by enemy intercontinental ballistic missiles.

Talos SAM Defense Unit is a land-based version of the Navy's Talos Shipboard Missile System.

1D3. Air Force missiles

Matador SSM is a tactical missile driven by a turbojet engine at a speed of 650 mph. It has a length of about 29 ft and a wing span of about 40 ft. It can carry a nuclear warhead, and may be guided by radio command or by a navigational system. Its range is more than 650 miles. Tactical missile groups armed with Matador are now deployed in Europe and on Formosa.

Falcon AAM comes in two versions, one with radar guidance and the other with infrared homing. Falcon is a supersonic missile, propelled by a solid-fuel rocket. It weighs about 100 pounds, and is about 6 ft long.

Genie AAM is a rocket-propelled air defense missile that may be armed with a nuclear warhead.

Snark SSM is actually a pilotless aircraft. It can carry a nuclear warhead at high subsonic speed. Snark has an inertial or other navigational guidance system. In tests it has been accurately placed on a target at a range of 5,000 miles.

Rascal ASM is a rocket-powered missile 32 ft long and 4 ft in diameter. It is designed for launching from B-47 Stratojet bombers at

high altitude and high speed, at such a distance from the target that the bombers and crews are not exposed to local defenses.

Bomarc SAM is a long-range air defense missile that can destroy attacking aircraft at ranges of more than 100 miles, and altitudes above 60,000 ft. The missile is about 47 ft long, has a wing span of about 18 ft, and weighs about 15,000 pounds. It is launched vertically by solid-fuel boosters, and sustained in flight by twin ram-jet engines.

Thor SSM is the Air Force's intermediate range ballistic missile (IRBM). It is propelled by a liquid-fuel rocket at a speed of Mach 10; range is over 1,500 miles. Thor is provided with an inertial guidance system.

Atlas SSM is an intercontinental ballistic missile with a range of more than 5,000 miles. It is launched by rocket engines that develop many tons of thrust, and millions of horsepower, within a few seconds. Atlas reaches a top speed of about Mach 15—more than 10,000 miles an hour. It will descend on its target at that speed, from a height of about 800 miles.

Titan SSM is also an intercontinental ballistic missile. In general it is similar to Atlas, except that Titan has a second-stage motor. It is likely that one of these two missiles will be discontinued, and all the effort now going into both developments will be concentrated on only one of them.

Minuteman SSM is a solid-fuel intercontinental ballistic missile that will eventually replace both Atlas and Titan.

1D4. Navy missiles

Sidewinder AAM (fig. 1D1) is probably the simplest and cheapest of all guided missiles. It is about 9 ft long, and weighs about 155 pounds. It has only about 24 moving parts, and no more electronic parts than a table radio. It attains a speed of Mach 2 relative to the launcher, and a range of several miles; it is designed to destroy high-performance aircraft from sea level to altitudes above 50,000 ft. It has an infrared homing system. Sidewinder was named after a desert rattlesnake. (The Sidewinder snake, like all of the pit vipers, has infrared receptors on its head that enable it to detect the presence of prey by its body heat.) Sidewinder is now the primary airborne missile used by squadrons in the Sixth Fleet in the Mediterranean, and the Seventh Fleet in the Western Pacific.

Figure 1D1.—Sidewinder missile and pilot with pressure suit.

Sparrow I AAM is 12 ft long and weighs 300 pounds; it reaches a speed of Mach 2.5 relative to the launcher, within a few seconds after launching. It is provided with beam-rider guidance, and is propelled by a solid-fuel

rocket. Navy planes can carry two to four of the missiles, and can fire them singly or in salvos.

Sparrow II AAM was developed as an experimental missile, and not intended to become operational. It has, however, been adopted for operational use by the Royal Canadian Air Force.

Sparrow III AAM is very similar to Sparrow I, but with a much more sophisticated guidance system. It is slightly heavier than Sparrow I, a little faster, and has a longer range. It will first supplement, and then replace Sparrow I in the Fleet.

Petrel ASM is nearly obsolete; although a few of these missiles may still be found in the Fleet, they are no longer in production. Petrel is a subsonic missile with radar homing, powered by a turbojet engine. Its payload is not a warhead, but a homing torpedo.

Bullpup ASM is 11 ft long and weighs about 540 pounds. It is relatively inexpensive, simple in design, and extremely accurate. Bullpup is a tactical missile with a conventional warhead, designed for use by carrier-based aircraft against small targets such as pillboxes, tanks, and truck convoys, in support of ground troops. It is powered by a solid-fuel rocket, and has a range of 15,000 ft at a speed of Mach 2.

Corvus ASM is a supersonic missile, propelled by a solid-fuel rocket, and designed for use by carrier-based aircraft. No further details have been released.

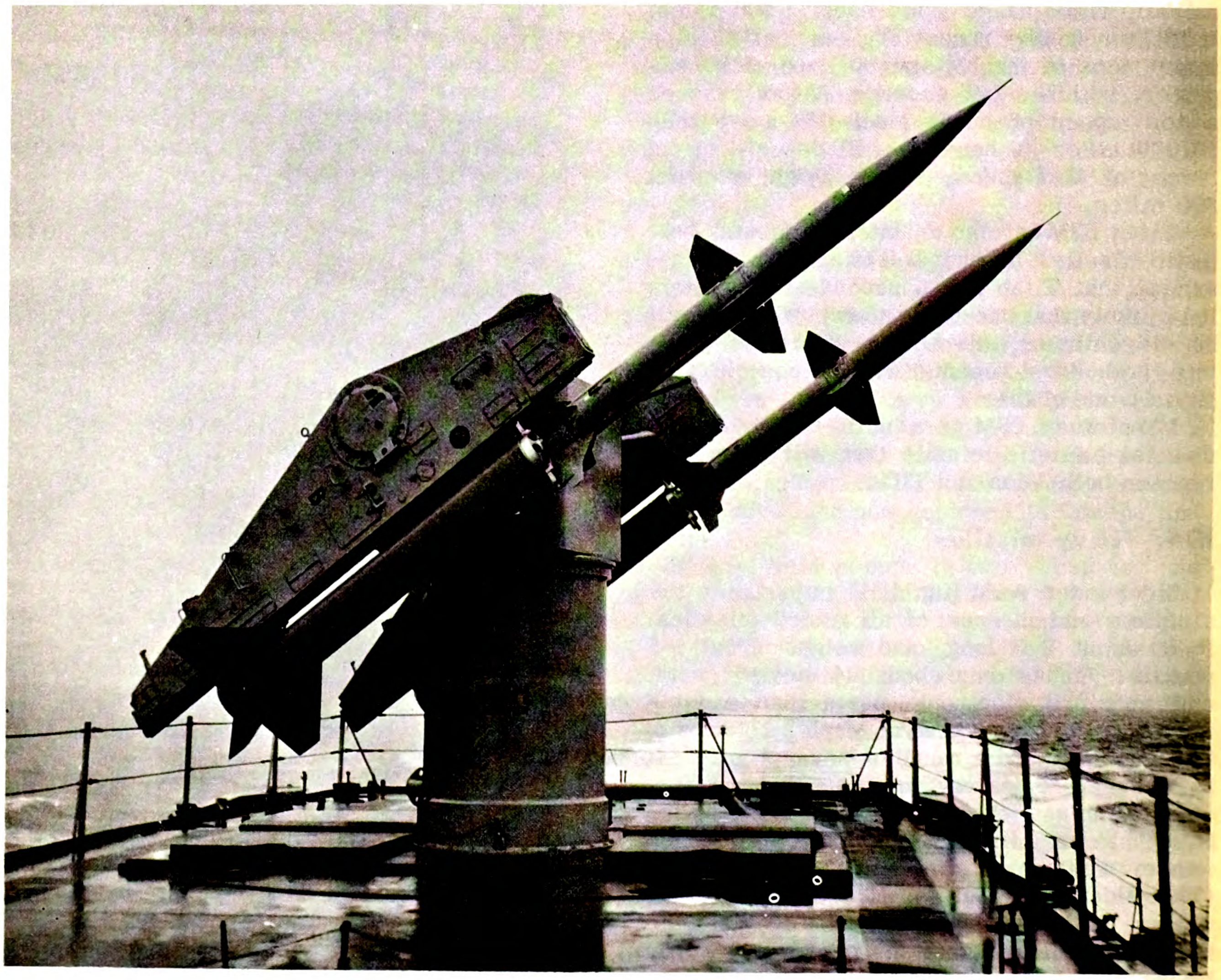

Figure 1D2.—Terrier missiles and launchers.

Terrier SAM (fig. 1D2) is a supersonic beam-riding antiaircraft missile with a range of more than 10 miles. It is launched by a solid-fuel booster rocket, and propelled by a solid-fuel sustainer rocket. Terrier is about 15 ft long without its booster, and weighs 1-1/2 tons. Terrier batteries have been installed on the guided missile cruisers *Boston* and *Canberra*, and on the guided missile destroyer *Gyatt*. Terriers will be used by the aircraft carriers *Kitty Hawk* and *Constellation*, cruisers *Topeka*, *Providence*, and *Springfield*, the nuclear cruiser *Long Beach*, and frigates *Farragut*, *Luce*, *MacDonough*, *Coontz*, *King*, *Mahan*, and *Dewey*.

Tartar SAM is similar in function to Terrier; except it is propelled by a dual-thrust rocket, and is launched without a booster. The Tartar system will be installed aboard the guided missile destroyers 2 through 14, and aboard the cruisers *Chicago*, *Albany*, and *Fall River*.

Talos SAM (fig. 1D3) is designed to bring down attacking enemy aircraft and missiles at ranges of 65 miles or more. It is 20 ft long, and weighs 1-1/2 tons. It is launched with solid-fuel boosters, and sustained in flight by a ram-jet; it reaches a speed in excess of Mach 2 within about 10 seconds of launching. It can be armed with a nuclear warhead. During the first part of its flight, Talos is a beam rider. As it approaches its target, it switches over to homing guidance. Talos systems are now installed on the cruisers *Galveston*, *Little Rock*, and *Oklahoma City*. It is scheduled for installation on the cruisers *Albany*, *Fall River*, and *Chicago*, and on the nuclear powered cruiser *Long Beach*.

Regulus I SSM (fig. 1D4) is intended primarily for use against enemy shore installations, but it can also be used against ships. Regulus I is about 30 ft long, and resembles a conventional swept-wing fighter aircraft. It is powered by a turbojet engine, and flies at the speed of Mach 1 for a range of about 500 miles. It can be armed with a nuclear warhead. Launching equipment for this missile can be installed in a short time on several types of ships, at relatively low cost and with little modification of the ship itself. Among the ships that can now launch Regulus I are the cruisers *Macon*, *Helena*, *Toledo*, and *Los Angeles*, submarines *Tunny* and *Barbero*, and carriers *Randolph*, *Hancock*, *Forrestal*,

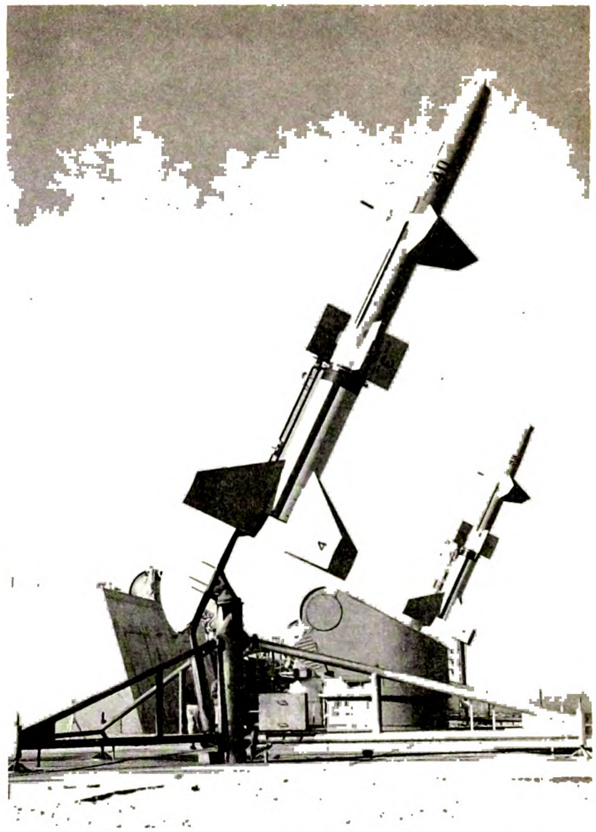

Figure 1D3.—Talos missiles on launcher at White Sands Proving Ground.

Saratoga, *Lake Champlain*, *Franklin D. Roosevelt*, *Lexington*, *Bennington*, *Bon Homme Richard*, and *Shangri-La*. Two different versions of Regulus I have been developed. The tactical version is nonrecoverable. The test version is provided with retractable landing gear and parachute braking. It can be launched and recovered repeatedly—a factor that drastically reduces the cost of evaluating and testing the missile system.

Regulus II SSM (fig. 1D5) is 57 ft long, and has a 20-ft wingspan. It is propelled by a turbojet engine with afterburner at a speed of Mach 2. Its range is more than 1,000 miles, and its altitude capability more than 60,000 ft. Like Regulus I it can carry a nuclear warhead, and is made in both a tactical and a recoverable test version. Regulus II may be guided by either a command system or an inertial navigation system. Unlike ballistic missiles, which are capable of only one path of approach to a target, Regulus can be guided to its target

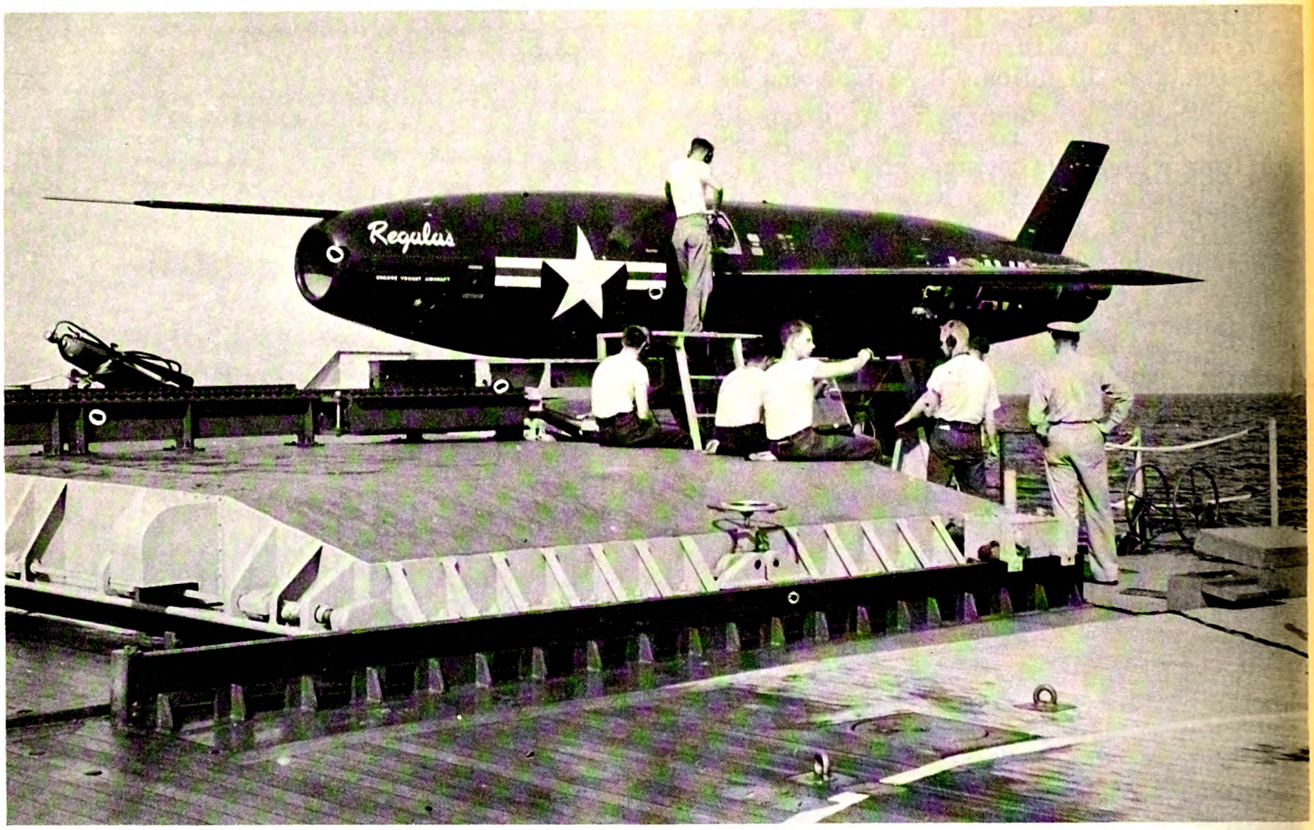

Figure 1D4.–Regulus I on fantail of USS *Helena* (CA-75).

in any of a number of ways. For example, it may approach at 60,000 feet, and then descend to 500 feet when it approaches within 50 miles of the target. It may power-dive vertically onto the target from 60,000 feet. Or it may approach the target at low altitude, and then climb to high altitude before diving. It can change target in mid-flight. It can be launched at the first indication of enemy attack, and then called back in the event of a false alarm.

However, due to budgetary limitations the Regulus II program has been cancelled. The remaining Regulus II missiles will be used in other missile programs as high speed targets.

Polaris SSM-USM (fig. 1D6) is the Navy's intermediate-range ballistic missile, with a range of about 1,500 miles. It is designed for launching either from surface ships or from submerged submarines. It is propelled by solid fuel. There are, at present, plans to build nine submarines capable of launching Polaris. Each submarine will carry 10 or more missiles.

Figure 1D5.—Regulus II missiles (test version).

Figure 1D6.—Polaris

CHAPTER 2
FACTORS AFFECTING MISSILE FLIGHT
A. Introduction

2A1. General

A guided missile, by definition, flies above the surface of the earth. Aerodynamic long-range missiles, as well as all missiles of short and medium range, are subject throughout their flight to the forces imposed by the earth's atmosphere. Ballistic missiles, though they follow a trajectory that takes them into space, must climb through the atmosphere after launching, and must descend through it before striking the target. All missiles are subject to gravitational and inertial forces. This chapter will briefly discuss the principal forces that act on a guided missile during its flight. It will show how the missile trajectory may be controlled by designing the missile airframe and control surfaces to utilize or overcome the forces acting on them.

An understanding of missile aeroaynamics requires a familiarity with several of the basic laws of physics. These laws will be briefly summarized. A detailed study of air in motion, and the mathematical analysis of the various forces present, are beyond the scope of this text. The discussion will be general and qualitative, and no mathematical development will be attempted.

In general, missile aerodynamics are the same for both subsonic and supersonic flight. The basic requirement is common to all craft intended to fly: in order to fly successfully, the craft must be aerodynamically sound. But the high speeds and high altitudes attained by current guided missiles give rise to new problems not encountered by most conventional aircraft. An example is the shock wave that is produced when a flying object attains the speed of sound. Problems of oxygen supply for air breathing missiles arise at high altitudes, and problems of skinheating by friction with the air arise at high speeds.

B. Physics of Flight

2B1. Forces acting on a missile in flight

Gravity, friction, air resistance, and other factors produce forces that act on all parts of a missile moving through the air. One such force is that which the missile exerts on the air as it moves through it. In opposition to this is the force that the air delivers to the missile. The force of gravity constantly attracts the missile toward the earth, and the missile must exert a corresponding upward force to remain in flight.

Figure 2B1 illustrates the forces acting on a body in level flight through the air, at a uniform speed. Note that the force tending to produce motion (toward the left) exactly balances that resisting the motion. The force of gravity is exactly opposed by the lifting force. In accordance with Newton's first law (discussed below), a moving body on which all forces are balanced will continue to move in the same directions and at the same speed.

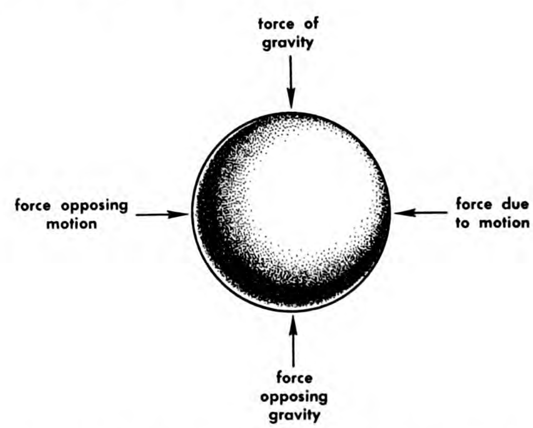

Figure 2B1.—Forces acting on a body moving through air.

Figure 2B2 illustrates the effect of unbalanced forces acting on a body. The length of the arrows is proportional to the respective magnitude of the forces, and the arrowheads point in the direction in which these forces are applied. The illustration shows that forces

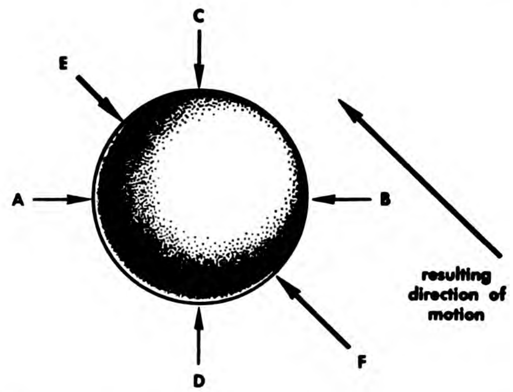

Figure 2B2.–Unequal forces acting on a body.

A and B are equal and opposite, and that C and D are equal and opposite. But force F is opposite to and greater than force E. As a result, the body shown will accelerate in the direction of force F. This figure is an example of vector representation of the forces acting on a body. Any number of forces may be shown by vector representation. They can be resolved, or simplified, into resultant force that is the net effect of all the forces applied.

2B2. Relativity of motion

To an observer standing on the ground and watching the flight of a missile through the air, it appears that the missile is moving and the air standing still. It would seem that the opposing force exerted by the air is entirely the result of the missile motion through it. But if it were possible for an observer to ride the missile itself, it would appear that the missile is standing still, and that the air is moving past the missile at high speed.

This illustrates the basic concept of relativity of motion. The forces that the air exerts on the missile are the same, regardless of which is considered to be in motion. The force exerted by the air on an object does not depend on the absolute velocity of either but only on the relative velocities between them. This principle can be put to good use in the study of missile aerodynamics, and in the design of missile airframes and control surfaces. In a wind tunnel, the missile or model remains stationary, while air moves past it at high speed. The measured forces are the same as those that would result if the missile, or model, were moving at the same relative speed through a stationary mass of air.

2B3. Newton's laws of motion

Newton's first law states: "A body in a state of rest remains at rest, and a body in motion remains in uniform motion, unless acted upon by some outside force." This means that if an object is in motion, it will continue in the same direction and at the same speed until some unbalanced force is applied. And, whenever there are unbalanced forces acting on an object, that object must change its state of motion. For example, if you were to push against a book lying on a table, you would have to supply sufficient force to overcome friction in order to set the book in motion. If you would eliminate all of the restraining forces acting on the book once it is in motion, it would continue to move uniformly until acted upon by some outside force. It is these restraining forces with which we are mainly concerned in the study of aerodynamics.

Newton's second law states: "The rate of change in momentum of an object is proportional to the force acting on the object, and in the direction of the force." The momentum of an object may be defined as the force that object would exert to resist any change of its motion.

Newton's third law states: "To every action there is an equal and opposite reaction." This law means that when a force is applied to any object, there must be a reaction opposite to and equal to the applied force. If an object is in motion, and we try to change either the direction or rate of that motion, the object will exert an equal and opposite force. That force is directly proportional to the mass of the object, and to the change in its velocity. This can be stated as:

Force = Mass times Acceleration,

or

$$F = ma$$

Thus any object in motion is capable of exerting a force. Whenever a force is applied through a distance, it does work. We can express this as:

Work = Force times Distance

or

$$W = Fd$$

Any mass that is in motion is capable of applying a force over a distance, and therefore of doing work. Whenever the motion of a mass is changed, there is, in accordance with Newton's second law, a change in momentum.

2B4. Lift and drag

Figure 2B3 represents a flat surface moving through an airstream. In accordance with the principle of relativity, the forces acting on the surface are the same, regardless of whether we think of the surface as moving to the left, or of the airstream as moving to the right. One of the forces acting on the surface is that produced by friction with the air. This force acts in a direction parallel to the surface, as indicated by the small white arrow at the lower right. As the air strikes the surface, it will be deflected downward. Because the air has mass, this change in its motion will result in a force applied to the surface. This force acts at a right angle to the surface, as indicated by the long black arrow in figure 2B3. The resultant of the frictional and deflection forces, indicating the net effect of the two, is represented by the long white arrow. We can resolve this resultant force into its horizontal and vertical components. The horizontal component, operating in a direction opposite to the motion of the surface, is drag. The vertical force, operating upward, is lift. The angle that the moving surface makes with the air stream is the angle of attack. This angle affects both the frictional and the deflection force, and therefore affects both lift and drag.

Bernoulli's theorem states that the total energy in any system remains constant. Air flowing past the fuselage or over the wing of a guided missile forms a system to which this theorem can be applied. The energy in a given air mass is the product of its pressure and its velocity. If the energy is to remain constant, it follows that a decrease in velocity will produce an increase in pressure, and that an increase in velocity will produce a decrease in pressure.

Figure 2B4 represents the flow of air over a wing section. Note that the air that passes over the wing must travel a greater distance than air passing under it. Since the two parts of the airstream reach the trailing edge of the wing at the same time, the air that flows over the wing must move faster than the air that flows under. In accordance with Bernoulli's theorem, this results in a lower pressure on the top than on the bottom of the wing. This pressure differential tends to force the wing upward, and gives it lift.

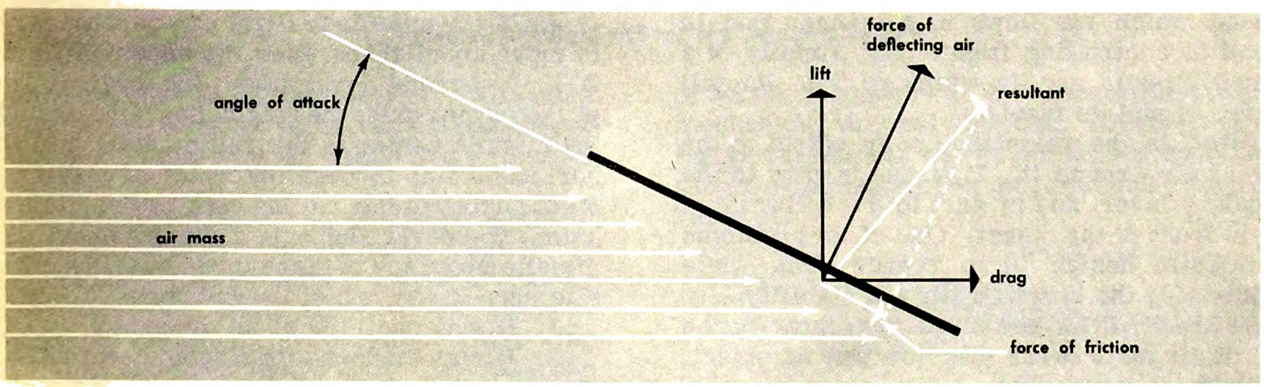

Figure 2B3.—Forces acting on a flat surface in an airstream.

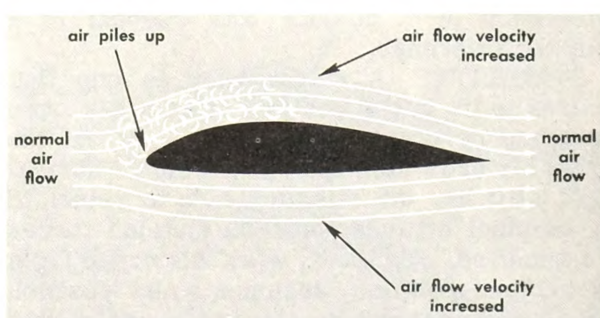

Figure 2B4.—Airflow over a wing section.

Figure 2B4 represents the general shape of a section of the wing of a conventional aircraft. In such an aircraft, the major part of the necessary lift is provided by the Bernoulli effect. As we will explain later, a wing of this shape is not suitable for use on missiles flying at or above the speed of sound. None of the Navy missiles listed in chapter 1 depends on a wing of this shape for lift. All of them get the necessary lift entirely from the angle of attack, as illustrated in figure 2B3.

Boundary layer refers to a condition that occurs as a result of friction between an airfoil surface and the air moving past it. The air tends to cling to the surface. This is a serious problem in missile design. Since lift depends on the flow of air past the surface, reduction in flow produces a reduction in lift. The boundary layer effect has been overcome to some extent by using highly polished surfaces, as free as possible from any irregularities.

C. Aerodynamic Forces

2C1. Terminology

A discussion of the problems of aerodynamic forces involves the use of several flight terms that require explanation. The following definitions are intended to be as simple and basic as possible. They are not necessarily the definitions an aeronautical engineer would use.

AIRFOIL. An airfoil is any structure around which air flows in a manner that is useful in controlling flight. The airfoils of a guided missile are its wings or fins, its tail surfaces, and its fuselage.

DRAG is the resistance of an object to the flow of air around it. It is due in part to the boundary layer, and in part to the piling up of air in front of the object. One of the problems of missile design is to reduce drag while maintaining the required lift and stability.

STREAMLINES are lines representing the path of air particles as they flow past an object, as shown in figure 2B4.

WING SPAN is the measured distance from the tip of one wing to the tip of the other.

ATTITUDE. This term refers to the orientation of a missile with respect to a selected reference.

STABILITY. A stable body is one that returns to its initial position after it has been disturbed by some outside force. If outside forces disturb a stable missile from its normal flight attitude, the missile tends to return to its original attitude when the outside forces are removed. If a body, when disturbed from its original position, assumes a new position and neither returns to its origin nor moves any farther from it, the body is said to be neutrally stable. If the attitude of a neutrally stable missile is changed by an outside force or by a change in its controls, the missile remains in the new position until other forces influence it.

A third type of stability is negative stability, or instability. In this case a body displaced from its original position tends to move even farther away. For example, if an unstable aircraft is put into a climb, it tends to climb more and more steeply until it stalls.

AXIS. A missile in flight can be considered to move about three axes, as shown in figure 2C1. In normal level flight, the vertical line is the yawing axis; the longitudinal line through the missile center is the rolling axis; and the horizontal line through the center of gravity at right angles to the rolling axis is the pitching axis. Whenever there is a displacement of a missile about any of these three axes, the missile may do any one of the following:

1. It may oscillate about the axis.
2. It may increase its displacement and get out of control.
3. It may return to its original position readily, without oscillation.

The last possibility, which indicates a stable missile, is the one desired. We will show later how this problem of stability is met in missile design.

2C2. Effects of aerodynamic forces

CENTER OF PRESSURE. On every point of a moving airfoil, a small force is present. This force is different in both magnitude and direction from that acting on any other point on the airfoil. It is possible to add mathematically all of these small forces. Their sum is the resultant force. The resultant has

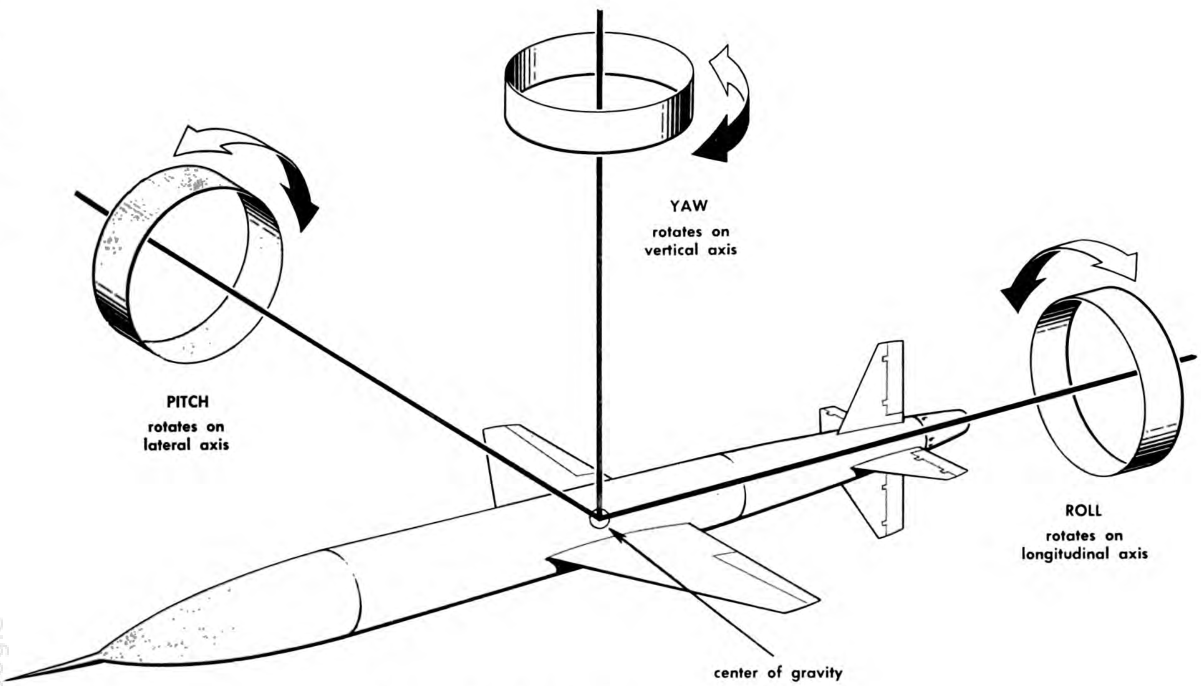

Figure 2C1.–Flight attitude of a guided missile.

magnitude, direction, and location. The point at which the resultant force can be considered as applied to the wing is called the center of pressure.

In actual flight, a change in the angle of attack will change the airspeed. But if for test purposes we maintain a constant velocity of the airstream while changing the angle of attack, the results on a nonsymmetrical wing will be as shown in figure 2C2. The sketches show a wing section at various angles of attack, and the effect of these different angles on the resultant force and the position of the center of pressure.

The burble point referred to in the lower sketch is the point at which airflow over the upper surface becomes rough, causing an uneven distribution of pressure. The burble point is generally reached when the angle of attack is increased to about 18° or 20°. At small angles of attack, the resultant is comparatively small. Its direction is upward and back from the vertical, and its center of pressure is well back from the leading edge. Note that the center of pressure changes with the angle of attack, and the resultant has an upward and backward direction. At a positive angle of attack of about 3° or 4°, the resultant has its most nearly vertical direction. Either increasing or decreasing the angle causes the direction of the resultant to move farther from the vertical.

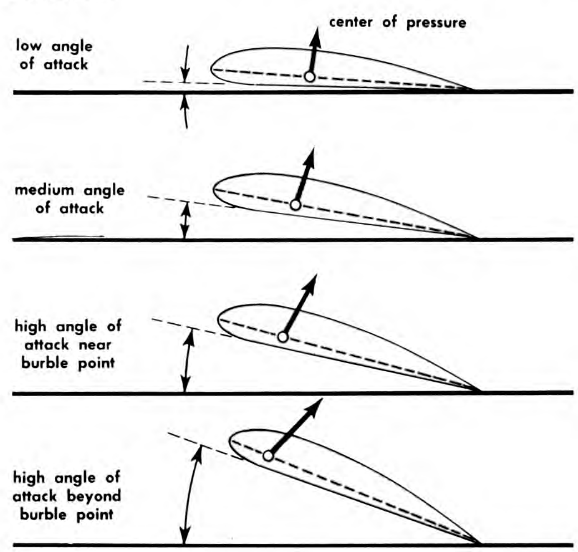

Figure 2C2.–Effect of angle of attack on center of pressure.

As we have shown, the resultant force on a wing can be resolved into forces perpendicular and parallel to the relative wind; these components are lift and drag. The lift force depends on the contour of the wing, the angle of attack, air density, area of the wing, and the square of the air speed. If a missile is to continue in level flight, its total lift must equal its weight. As the angle of attack increases, the lift increases until it reaches a maximum value. At the angle of maximum lift, the air no longer flows evenly over the wing, but tends to break away from it. This breaking away (the burble point) occurs at the stalling angle. If the angle of attack is increased further, both lifting force and airspeed decrease rapidly.

Drag is the resistance of air to motion through it. The drag component of the resultant force on a wing is the component parallel to the direction of motion. This force resists the forward motion of the missile. If the missile is to fly, drag must be overcome by thrust—the force tending to push the missile forward. Drag depends on the missile area, the air density, and the square of the velocity. Air resists the motion of all parts of the missile, including the wings, fuselage, tail airfoils, and other surfaces. The resistance to those parts that contribute lift to the missile is called induced drag. The resistance to all parts that do not contribute lift is parasitic drag.

From Newton's laws, we know two things: First, if all the forces applied to a missile are in balance, then if the missile is stationary it will remain so; if it is moving, it will continue to move in the same direction at the same speed until an outside force is applied to it. Second, if an unbalanced force—one not counteracted by an equal and opposite force—is applied to the missile, it will accelerate in the direction of the unbalanced force.

At the instant of launching, missile speed is zero, and there is no drag. (We will, for the moment, disregard air-launched missiles.) The force of thrust developed by the propulsion system will be unbalanced, and as a result the missile will accelerate in the direction of thrust. (A solid-fuel rocket develops full thrust almost instantly. When a long-range liquid-fuel rocket is launched, it may be physically held down until its engines have developed sufficient thrust.) When thrust weight ratio reaches its maximum value, acceleration of the missile is at a maximum. But, during the launching phase, missile speed quickly increases. Because drag is proportional to the square of the speed, drag increases very rapidly. The force of thrust is thus opposed by a steadily increasing force of drag. The missile will continue to increase in speed, but its acceleration (rate of increase of speed) will steadily decline. This decline will continue until thrust and drag are exactly in balance; the missile will then fly at a uniform speed as long as its thrust remains constant.

If the propulsive thrust is decreased for any reason (such as a command from the guidance system, or incipient fuel exhaustion) the force of drag will exceed the thrust. The missile will slow down until the two are again in balance. When the missile fuel is exhausted, or the propulsion system is shut down by the guidance system, there is no more thrust. The force of drag will then be unbalanced, and will cause a negative acceleration, resulting in a decrease in speed. But, as the speed decreases, drag will also decrease. Thus the rate of decrease in speed also decreases.

As we have shown, a missile will maintain a uniform forward motion when thrust and drag are equal. The power required to maintain uniform forward motion is equal to the product of the drag and the speed. If drag is expressed in pounds, and speed in feet per second, the product is power in foot-pounds per second. By definition, one horsepower is 550 foot-pounds per second. The horsepower expended by a missile in uniform forward motion is then

$$hp = \frac{DV}{550}$$

where D is the drag in pounds, and V the speed in feet per second.

2C3. Problems of missile control

A missile must be so designed and constructed that it will fly a specified course without continual changes in direction. The degree of stability of a missile has a direct effect on the behavior of its controls, and for this reason a high degree of stability must be maintained. As the speed of a missile increases, its stability is changed by shifts in the center of pressure. A pressure shift causes changes in the airflow acting on the missile surfaces. Even

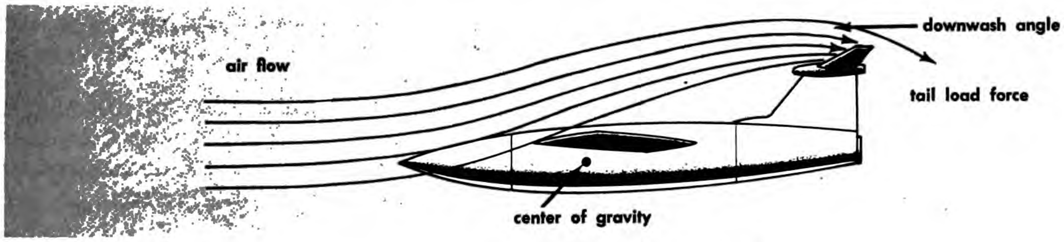

Figure 2C3.–Downwash.

in pure supersonic flow, variations in speed will cause shifts in center of pressure.

Figure 2C3 represents a missile in level flight; it is longitudinally stable about its lateral axis through the center of gravity. Airflow over the wing is deflected downward toward the elevator. This angle of deflection is called the downwash angle. When lift decreases as a result of reduced speed, this downwash angle decreases, and produces pressure changes. There will be certain speeds at which unstable conditions are set up as a result of such pressure shifts. When an unstable condition occurs, the control system must quickly compensate by moving the control surfaces or changing the missile speed; otherwise the missile may get out of control.

As we will show in the next section of this chapter, unstable conditions are most serious at transonic speeds. Most missiles have dive control and roll recovery devices to overcome unstable conditions. For example, the horizontal tail surfaces may be placed high on the fin, to minimize,the effects of downwash.

Unstable airflow over the wings of a missile may cause the ailerons to oscillate, creating a condition known as "buzz." A similar condition called "snaking" may exist about the yaw axis as a result of rudder oscillation. The troubles may be partially compensated for by nonreversible control systems, or by variable-incidence control surfaces.

STABILITY ABOUT THE VERTICAL AXIS is usually provided for by vertical fins. If a missile begins to yaw to the right, air pressure on the left side of the vertical fins is increased. This increased pressure resists the yaw, and tends to force the tail in the opposite direction. In some missiles the vertical fin may be divided, and have a movable part, called the rudder, that is used for directional control. In addition to the rudder, there may be trim tabs that can be set for a particular direction of flight relative to the prevailing wind. The vertical sides of the fuselage also act as stabilizing surfaces. the same action takes place here as on the fin, but with a lesser correcting force.

Another means for obtaining yaw stability is by sweepback of wings. Sweepback is the angle between the leading edge of a wing and a line at right angles to the longitudinal axis of the missile. If a missile yaws to the right, the leading edge of the left sweptback wing becomes more perpendicular to the relative wind, while the right wing becomes less so. This puts more drag on the left wing, and less on the right. The unbalanced drag at the two sides of the missile tends to force it back to its original attitude.

STABILITY ABOUT THE LONGITUDINAL AXIS may be provided by dihedral--an upward angle of the wings. As the missile starts to roll, the lift force is no longer vertical, but moves toward the side to which the missile is rolling. As a result, the missile begins to sideslip. This increases the angle of attack of the lower wing, and decreases that of the upper. Lift on the lower wing will therefore increase, while lift on the upper wing decreases. This unbalanced lift tends to roll the missile back to its original attitude.

STABILITY ABOUT THE LATERAL AXIS is accomplished by horizontal surfaces at the tail of the missile. The stationary part of these surfaces is the stabilizer; the movable part is the elevator. Pitch stability results from the change in forces on the stabilizer when the missile changes its angle of attack. For example, if the missile nose begins to pitch downward, the force of the airstream against the upper surface of the stabilizer will increase. This will tend to push the tail downward, and thus return the missile to its original attitude.

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D. Aerodynamics of Supersonic Missile Flight

2D1. Terminology

SHOCK WAVE. As a missile moves through the air, the air tends to be compressed, and to pile up in front of the missile. Because compressed air can flow at speeds up to the speed of sound, it can flow smoothly around a low-speed missile. But as the missile approaches the speed of sound, the air can no longer get out of the way fast enough. The missile surfaces split the airstream, producing shock waves. A shock wave is a sharp boundary between two masses of air at different pressures.

Shock waves can seriously alter the forces acting on a missile, requiring radical changes in trim. The missile tail surfaces may be seriously buffeted and wing drag rises. Any deflection of the control surfaces in an attempt to overcome these conditions may cause new shock waves, which interact with those already present. For this reason there may be certain speeds at which the controls become entirely useless.

MACH NUMBER is the ratio of flight speed to the speed of sound. It was named in honor of Ernst Mach (pronounced mock), an Austrian scientist who first pointed out its importance in 1887. If a missile travels at twice the speed of sound, it has a flight speed of Mach 2.0. If its speed is half that of sound, it has a flight speed of Mach 0.5. The speed of sound varies with both pressure and temperature. It decreases from an average of about 760 mph at sea level to about 675 mph at 30,000 feet.

REYNOLDS NUMBER. During the development of a new missile design, scale models of the proposed missile are tested in wind tunnels. But the performance of the model does not necessarily indicate the performance of the actual missile, even when all known variables are scaled down. In some cases the effect of a given variable on the model may be opposite to its effect on the full-size missile. Reynolds number is a mathematical ratio involving relative wind speeds, air viscoscity and density, relative sizes of the model and missile, and other factors. The use of this ratio makes it possible to predict missile behavior under actual flight conditions from the behavior of the model in the wind tunnel.

HEAT BARRIER is not a barrier in a physical sense, but its effect tends to limit the maximum speed of a missile through the atmosphere. Heat results not only from friction, but from the fact that at high speeds the air is compressed by a ram effect. The temperature rise caused by the ram effect is proportional to the square of the Mach number. The average temperature at sea level is considered to be 59°F; temperature decreases steadily with altitude to about 46,000 feet, above which it is assumed to be constant. At sea level, ram temperature is about 88°F at Mach 1—29° higher than the standard temperature. At Mach 2, ram temperature at sea level is about 260°F, and at Mach 4 about 1000°F. Missiles capable of flying at these speeds must be capable of withstanding these temperatures. This problem is particularly serious with ballistic missiles intended to plunge down into the atmosphere at speeds in the order of Mach 12. A significant part of the development effort for long-range ballistic missiles has been devoted to development of nose cones capable of withstanding extreme temperatures.

SPEED CLASSIFICATIONS. Missile speeds may be divided into four categories: subsonic, transonic, supersonic, and hypersonic. A missile is moving at subsonic speed when the relative velocity of air at all points on its surface is less than the speed of sound. In the transonic range of speeds, air moves over some parts of the missile at less than the speed of sound, and over other parts at more than the speed of sound. Under these conditions, shock waves are present; the airflow is turbulent, and the missile may be severely buffeted. A high-speed missile should be made to accelerate through the transonic zone in the least possible time, to prevent these disturbances. A missile is moving at supersonic speed when the relative speed of the air at all points of its surface is greater than the speed of sound. In supersonic flow, little turbulence is present.

When any object moves through the air, the molecules of air require a finite time to adjust themselves to its presence, and to readjust themselves after it has passed. This period of adjustment and readjustment is called the relaxation time. If the time required for a

missile to pass a given point is equal to or less than the relaxation time, the missile is moving at hypersonic speed. Relaxation time is longer at high altitudes, and the beginning of the hypersonic speed zone is correspondingly lower. Under most conditions, this zone begins somewhere between Mach 5 and Mach 10.

MACH ANGLE. This term is illustrated by analogy in figure 2D1, which represents a boat in four different conditions of motion over the surface of a lake. Assume that any wave or ripple formed on this lake will move at a speed of 10 mph. And, just for the purposes of this illustration, assume that Mach number means the ratio of boat speed to wave speed.

In the sketch at the upper left of figure 2D1, the boat is at rest. If the wind makes the boat bob up and down, the boat will generate a series of ripples that spread out in concentric circles at the rate of 10 mph. In the upper right sketch, the boat is moving at 5 mph (representing a speed of Mach 0.5). After the boat generates a ripple, it will move with respect to that

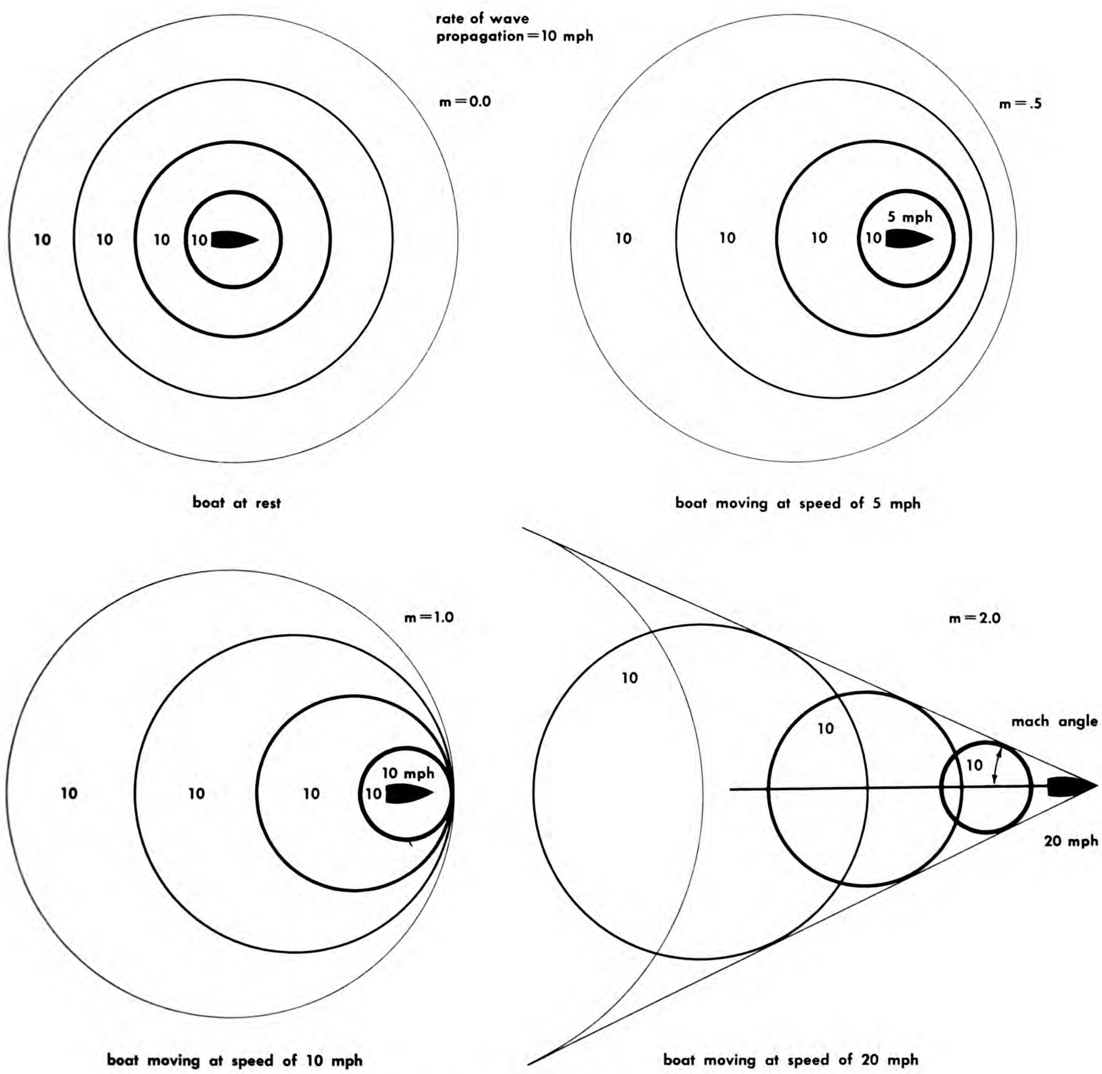


Figure 2D1.—Mach angle analogy.

ripple before it generates the next one. The waves still spread out at 10 mph, but they are no longer concentric.

A the lower left, figure 2D1, the boat is traveling at the speed of wave propagation, representing a speed of Mach 1.0. Because the boat is moving at the same rate the waves spread out, all the waves are tangent to each other at the bow of the boat. At the lower right, the boat is moving at Mach 2.0—twice the wave speed—and it leaves the ripples behind. The wave pattern now becomes a wedge on the surface of the water. In the air, with three dimensional flow, the pattern would be a cone. The semi-vertex angle is the MACH ANGLE. The greater the speed above Mach 1, the smaller the angle. The bow wave of the boat is closely analogous to the conical shock wave that spreads from the nose of a supersonic missile. And both have the same cause: the fact that an object is moving through a fluid faster than the fluid itself can flow.

NORMAL SHOCK WAVE. This term refers to a shock wave at a right angle to the direction of motion, that appears on any surface over which air is moving at the speed of sound. Figure 2D2 represents the flow of air over a section of a missile wing at four different speeds. In the upper sketch the missile is moving at subsonic speed. Air flows past every point on the wing at less than the speed of sound. The second wing section from the top is that of a missile in the transonic zone. The missile itself is moving at less than the speed of sound. But the air, in order to travel over the curved surface of the wing, must

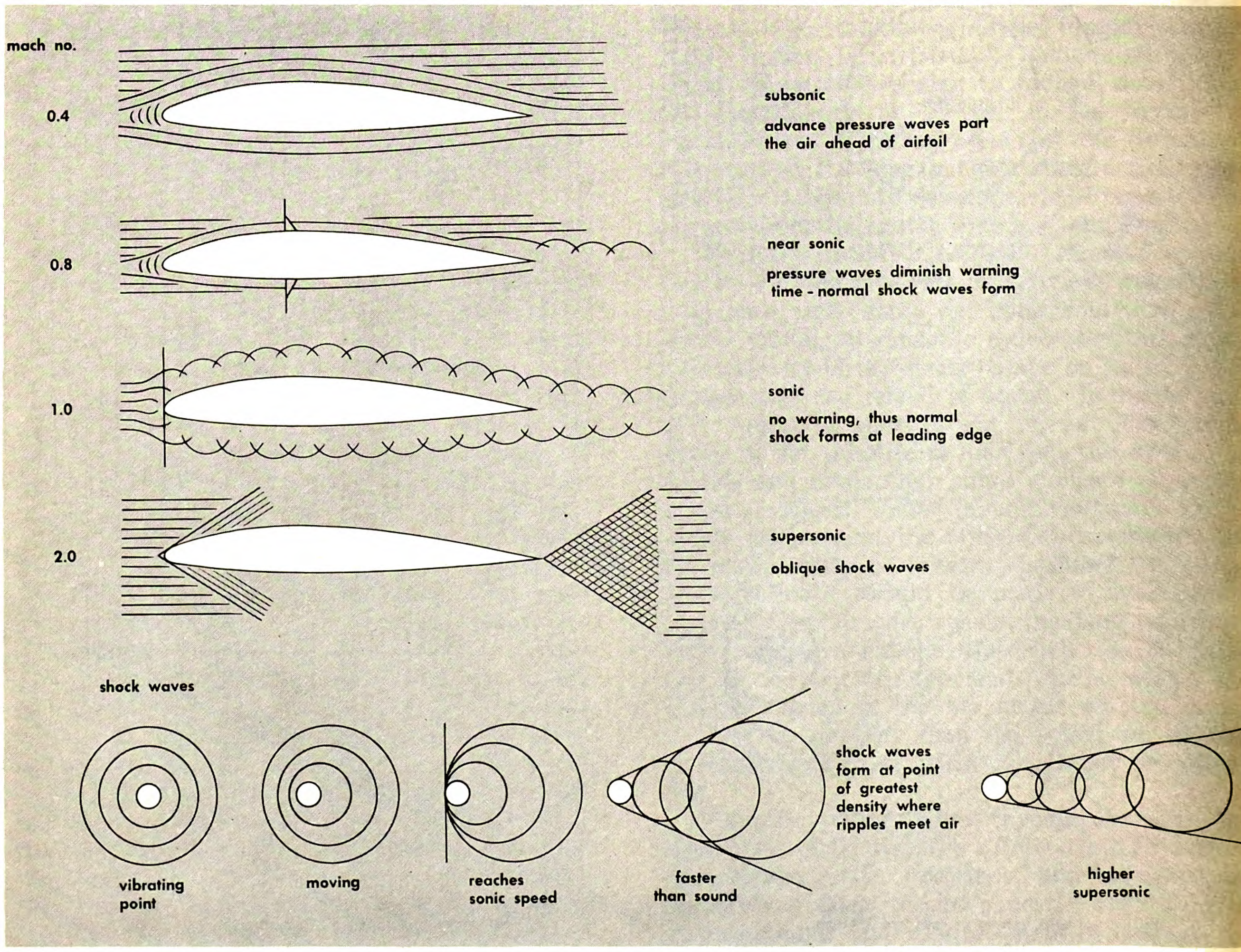


Figure 2D2.—Effect of missile speed on airflow pattern.

increase its relative speed. At a certain point on the curved surface it reaches the speed of sound, and a normal shock wave forms at that point.

The third wing section from the top (fig. 2D2) is moving at exactly the speed of sound. The normal shock wave now forms at the leading edge of the wing. Airflow over the whole wing surface is turbulent; lift and control are decreased, or lost altogether.

OBLIQUE SHOCK WAVE. The lowest of the four wing sections shown in figure 2D2 is moving at supersonic speed. The shock wave still forms at the leading edge of the wing; but now, because the missile is moving faster than the air can flow, the Mach angle is less than 90°, and an oblique shock wave spreads out from the leading edge of the wing. As we have said, a shock wave is a sharp boundary between two masses of air at different pressure. Air behind the oblique shock wave has a lower relative speed than that in front, and therefore has a higher pressure.

2D2. Control of supersonic missiles

Aerodynamic control is the connecting link between the guidance system and the missile flight path. Effective control of the flight path requires smooth and exact operation of the missile control surfaces. The control surfaces must have the best possible design configuration for the intended speed of the missile. They must be moved with enough force to produce the necessary change of direction. Methods must be found for balancing the various controls, and for changing them to meet the variations of lift and drag at different Mach speeds.

EXTERNAL CONTROL SURFACES. The simplest control surfaces are fixed fins. Fixed fins abaft the center of gravity provide "weathercock stability," in the same way that the feathers on an arrow give it a stable flight. Fixed fins are used on most current missiles. They are usually called vertical stabilizers or horizontal stabilizers, depending on their position and function.

All guided missiles are also provided with movable control surfaces, since stationary fins cannot provide the precise control needed to keep the missile on a desired course. Movable control surfaces can be divided into two types: primary and secondary. The primary controls include ailerons, elevators, and rudders. An aileron is attached to the trailing edge of the wing or main lifting surface, as shown at the upper right in figure 2D3.

The two ailerons move differentially. The three lower diagrams in figure 2D3 show how they control the roll of the missile about its longitudinal axis. With both ailerons in neutral position, both wings have the same lift. But when an aileron moves up, it decreases lift; when it moves down, lift increases. Thus, the wing with the raised aileron will move down and the other will move up, as shown in the diagram.

Figure 2D3 also shows the effect of the elevators and rudder. The elevators are the movable parts of the horizontal stabilizers; they control the movement of the missile about its axis of pitch. Both elevator surfaces move together. If they move down, they will deflect air downward from the tail. The tail will react by moving upward, and the nose of the missile will pitch downward.

The rudder consists of one or two movable surfaces on the trailing edge of the vertical stabilizer. If the rudder is in two parts, both move together. The rudder controls the movement of the missile about its axis of yaw. For example if the rudder moves to the right, the tail moves to the left, and the missile yaws to the right.

Secondary control surfaces include tabs, spoilers, and slots. A tab is a small independently movable surface on the trailing edge of a larger control surface. Tabs control the missile indirectly. For example, consider a tab on an elevator. If the tab moves upward, the deflected air will exert a downward force on the elevator. The elevator will then move down. Note that it is still the elevator, not the tab, that directly controls the missile.

A spoiler can be any of several devices—for example a hinged flap on the upper surface of the wing. Suppose that a gust of air causes the left wing to lose lift. The spoiler on the right wing can be raised to "spoil" the smooth flow of air over it, and thus decrease its lift to equal that of the other wing.

A slot is basically a high-lift device located at the leading edge of the wing. At a normal angle of attack, it has no effect. At high angles of attack the slot can be opened to allow air to spill through and thus prevent a stall.

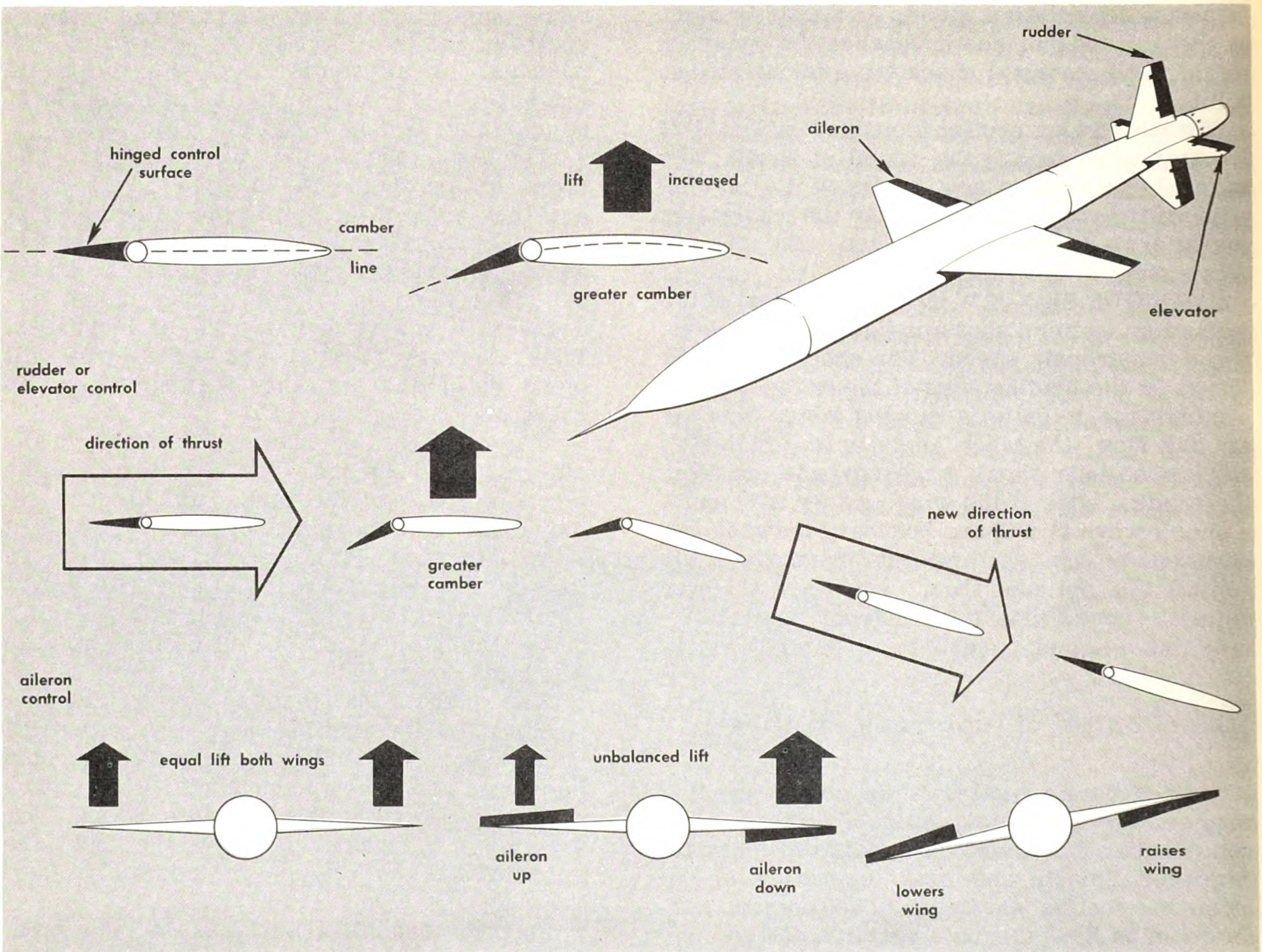


Figure 2D3.–Effect of control surfaces on missile flight.

DUAL PURPOSE CONTROL. In some types of missiles, two control functions are combined in a single set of control surfaces. Elevons (also called ailevators) combine the function of elevators and ailerons. Such surfaces might be mounted on the trailing edges of delta wings. If operated together, they serve as elevators; if operated differentially, they serve as ailerons. If the missile tail surfaces were inclined upward, to form a V with the missile axis, controls on the trailing edges of these surfaces could be used as ruddervators. By suitable combinations of movements, they could control the missile in both pitch and yaw.

CONTROL AT STARTING SPEEDS. Surface-launched missiles start out with zero velocity, and accelerate to flying speeds. For a short time after launching, airspeed over the control surfaces is slow, and these surfaces are unable to stabilize the missile or control its course. With small, booster-launched missiles, this problem is not serious. Terrier, for example, builds up enough speed for aerodynamic stability in a fraction of a second. But heavy intercontinental ballistic missiles rise slowly from their launching pads, and may require auxiliary control devices for a number of seconds after launching. Two types of auxiliary control have been used.

EXHAUST VANES are surfaces mounted directly in the exhaust path of a jet or rocket engine. When the exhaust vanes are moved, they deflect the direction of exhaust, and thus

produce a lateral component of thrust that can be used to keep the missile pointed in the desired direction. This is possible because the exhaust velocity is very high, even when the missile has just begun to move. Because of the tremendous heat in the exhaust, the life of exhaust vanes is short. The German V-2 used exhaust vanes made of carbon. The melting point of carbon is far above the exhaust temperature. But because carbon burns, the vanes were eroded rapidly. By the time the V-2 reached a speed at which the vanes were no longer needed, they were burned away completely.

JET CONTROL is similar to exhaust vane control in that both deflect the exhaust to produce a lateral component of thrust. One method of jet control consists in mounting the engine itself in gimbals, and turning the whole engine to deflect the exhaust stream. This system requires that the engine be fed by flexible fuel lines; and the control system that turns the engine must be very powerful. Another method of jet control consists in mounting several auxiliary jets at various points on the missile surface. By turning on one or more of the auxiliary jets, it is possible for the guidance and control systems to change the missile course as required. The use of auxiliary jets makes it possible to eliminate the outside control surfaces entirely. This is the steering method most likely to be used for control of missiles after they leave the atmosphere (and, eventually, for the control of space ships).

2D3. Effects of missile configuration

The configuration of a guided missile is the principal factor controlling the drag and lift forces that act on it. And these two forces largely determine the overall efficiency of the missile.

DRAG REDUCTION. It is essential that supersonic missiles be designed for minimum drag. A low drag configuration makes it possible to use a smaller power plant, with a lower rate of fuel consumption. The resulting saving in bulk and weight can be used to extend the range of the missile, add to its war head payload, reduce its over-all size, or any combination of these three.

The effects of thickness distribution, Reynolds number, surface imperfection, and Mach number all influence missile drag. Wing drag is influenced by thickness ratio, sweepback, aspect ratio, and section of airfoil. Total drag of the missile is made up of fuselage drag, wing and fin drag, and another factor not present in subsonic flight: mutual interference between the drags of the individual parts. For example, the drag of a wing may be strongly affected, for better or worse, by the shape of the body on which it is mounted.

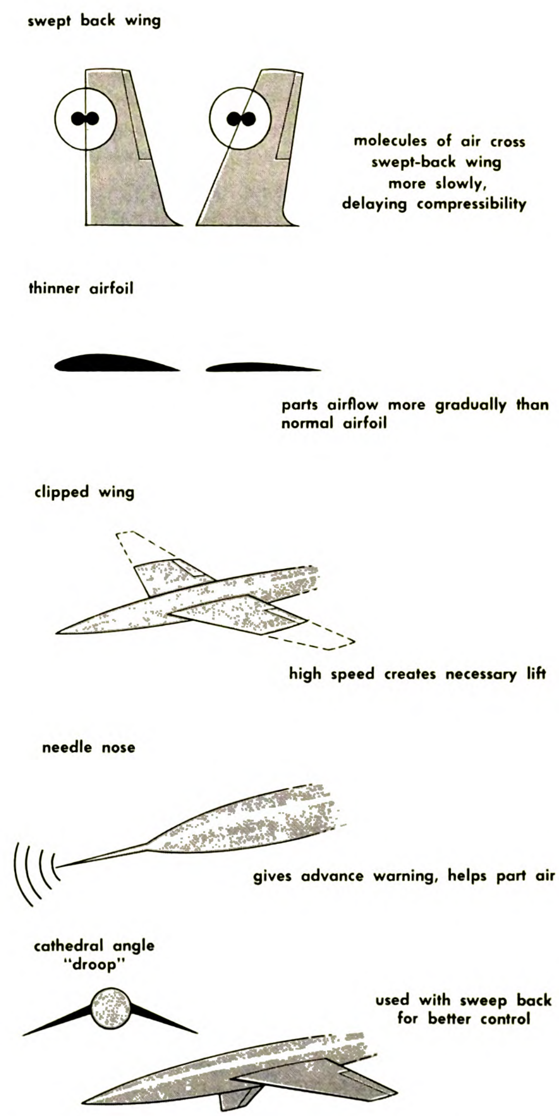


Figure 2D4.—High speed configuration characteristics.

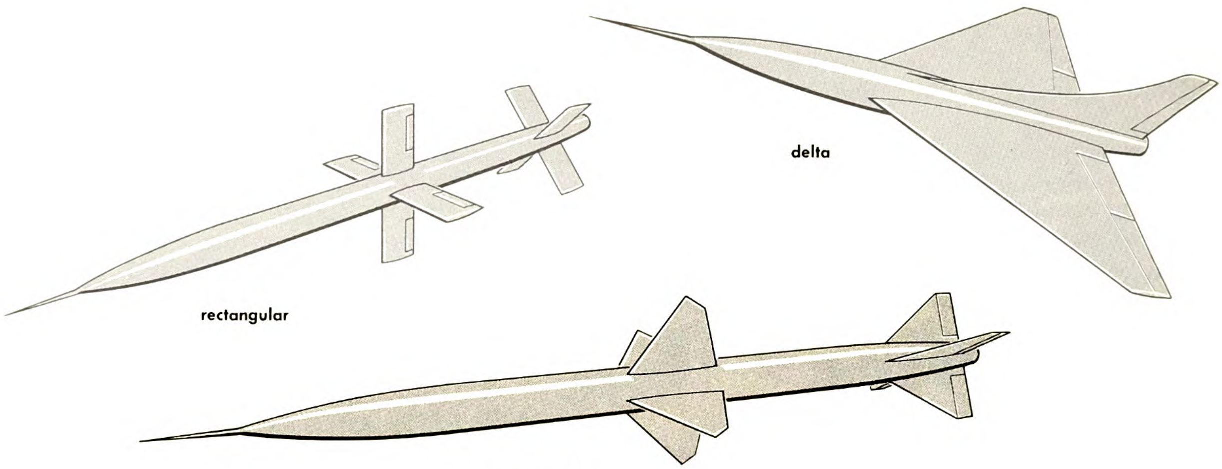


Figure 2D5.—Airfoil plan forms.

LIFT EFFECTIVENESS. A steady lift force, equal to the weight of the missile, must be maintained to keep the missile in level flight. Additional lift must be available for maneuvering. A missile must be so designed that the necessary lift is provided with minimum drag. And, for satisfactory control response, lift must vary smoothly with the angle of attack.

The conditions of flight associated with subsonic airflow are well known. Airflow phenomena at supersonic speeds are orderly, and can be analyzed mathematically. But in the transonic speed range, major design problems arise. A great deal remains to be learned about airflow in this range.

Airflow over an ideal wing would be subsonic until the missile reaches a velocity of Mach 1, and it would then immediately become supersonic. In other words, an ideal wing, if it were possible to make one, would eliminate the transonic range. Actually, the transonic range begins when the flow over any part of the missile becomes supersonic, and continues until the flow over all parts of the missile becomes supersonic. The free-stream Mach number at which transonic flow begins on any given missile is called the critical Mach number for that missile.

Every missile is designed for a cruising speed either below the transonic region or above it; no missile is intended to cruise within this region. For supersonic missiles, the effects of the transonic zone can be minimized in two ways. First, the range of speeds included within the transonic zone can be narrowed by suitable design of the missile. Figure 2D4 illustrates some of the devices that have been used for this purpose. Second, by maintaining maximum powerplant thrust until after supersonic velocity is reached, the missile can pass through the transonic region in minimum time. Supersonic missiles are often launched with the help of boosters. A booster may be considered as an auxiliary powerplant. It consumes fuel at a rapid rate, and develops a high thrust. After the missile has passed through the transonic region its booster falls away. The missile is then propelled at supersonic speed by its own powerplant, which has a lower rate of fuel consumption and a smaller thrust than the booster.

Figure 2D5 represents three common airfoil plan forms for guided missiles. The optimum arrangement of airfoils on a missile is governed by many factors, such as speed, rate of acceleration during the launching phase, range, and whether or not the missile is to be recovered. The sketches in figure 2D6 show some of the more common arrangements of missile airfoils. In some missile designs, arrangements shown in the figure as "tail units" may be used at the mid-section or even at the nose of the missile; in others, some of the "wing arrangements" shown in the figure may be used as tail units.

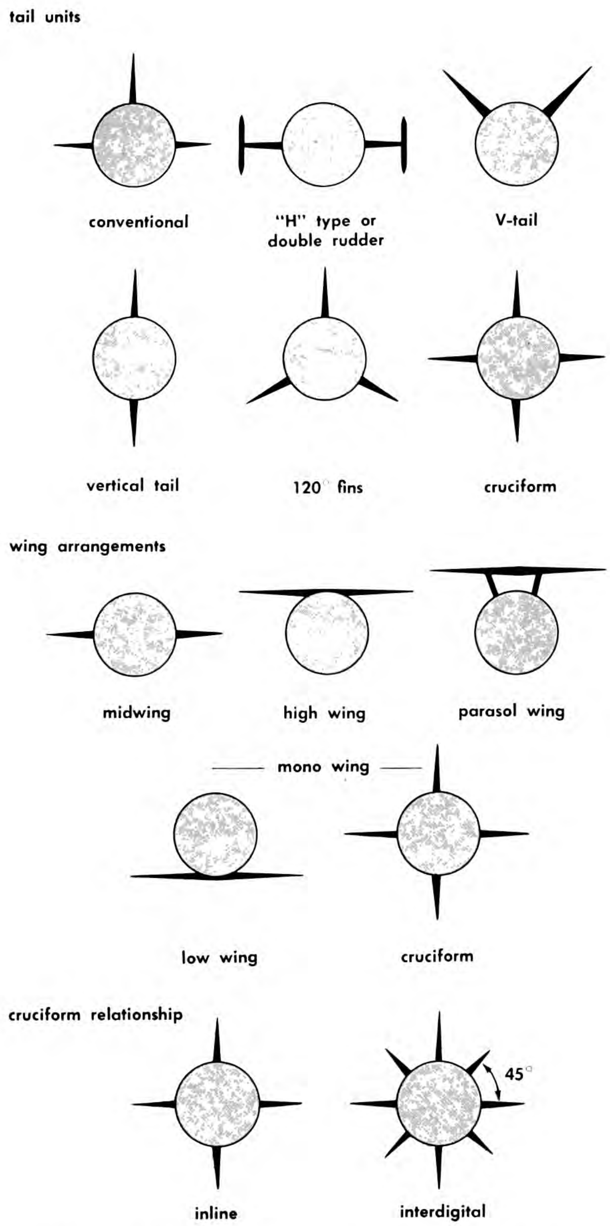


Figure 2D6.—Common arrangements of airfoils.

E. Guided Missile Trajectories

2E1. Trajectory curves

Missile trajectories include many types of curves. The exact nature of the curve is determined by the type of guidance and the nature of the control system used. For some missiles, the desired trajectory is chosen before the missile is designed, and the missile is closely limited to that trajectory. Other missiles, such as Regulus, may offer a choice of trajectories.

HYPERBOLIC SYSTEM. A missile using a hyperbolic guidance system will first climb to the desired altitude, then follow an arc of a hyperbola before diving on its target. If the control stations are ideally located with respect

to the target, the hyperbolic course is a close approach to a straight line. This system is described in a later chapter.

PURSUIT CURVE. Some homing missiles, and some beam riders, follow a pursuit curve. At any given instant, the course of the missile is directly toward the target. If missile and target are approaching head-on, or if the missile is engaged in a tail chase, the pursuit curve may be a straight line unless the target changes course. But a missile that pursues a crossing target must follow a curved trajectory. As the missile approaches a crossing target, the target bearing rate increases, and the curvature of the missile course increases correspondingly. In some cases the extreme curvature of the pursuit course may be too sharp for the missile to follow.

LEAD ANGLE COURSE. Some homing missiles follow a modified pursuit course. The deflection of the missile control surfaces is made proportional to the target bearing rate. The missile flies not toward the target, but toward a point in front of it. The missile thus develops a lead angle, and the curvature of its course is decreased.

A further refinement is possible if a computer, either in the missile or at a control station, can use known information about the missile and target to calculate a point of intercept which missile and target will reach at the same instant. Because the missile is guided directly toward the point of intercept, its trajectory is a straight line. If the target changes course during the missile flight, a new point of intercept will be calculated, and the missile course will be turned toward the new point of intercept.

BEAM-RIDER TRAJECTORY. As we will explain in a later chapter, a beam-rider missile may follow either a pursuit curve or a lead-angle course, depending on the type of system used.

FLAT TRAJECTORY. An intermediate-range or long-range air-breathing missile is usually made to climb as quickly as possible to the altitude at which its propulsion plant operates most efficiently—somewhere between 30,000 and 90,000 feet. After reaching this altitude the missile flies a flat trajectory to the target area. Regulus, for example, can be made to climb steeply to a desired altitude, level off, fly a flat trajectory to the target area, then dive straight down.

Figure 2E1 illustrates a probable trajectory for a long-range ballistic missile. The missile is launched vertically, so that it can get through

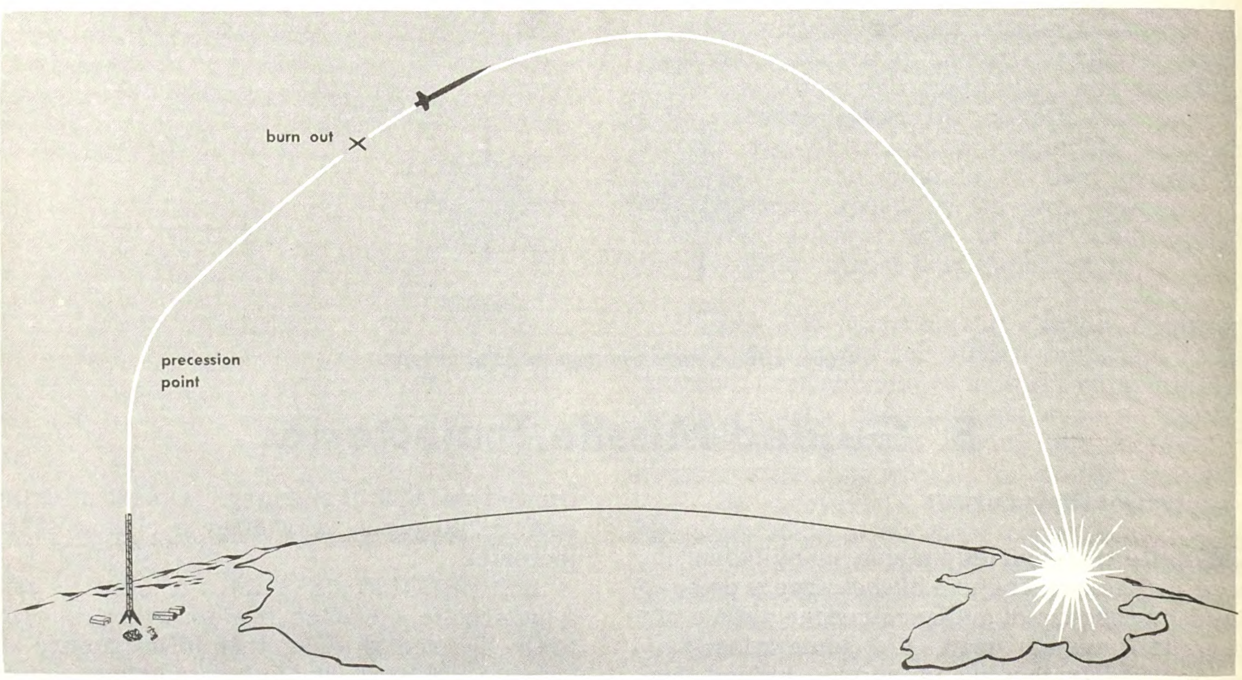


Figure 2E1.—High-angle rocket trajectory.

the densest part of the atmosphere as soon as possible. At a certain altitude which may be controlled by either preset or command guidance, the missile turns to a more gradual climb. After burnout, or shutdown, of the propulsion system by radio command, the missile "coasts" along a ballistic trajectory to the target.

2E2. Factors affecting missile trajectory

The principle factor affecting a missile's trajectory is, of course, the design of the missile and its guidance system. This article will deal only with other external forces affecting the trajectory. Such factors include wind, gravity, magnetic forces, and the coriolis effect. In the use of any long-range missile, all of these must be taken into account.

All missiles fly through the atmosphere, either during their entire flight or at the beginning and end of it. They are therefore liable to be pushed off the desired course by the force of the wind. The magnitude and direction of the prevailing winds at various points on the earth are well known. But the prevailing winds are much modified by a number of factors such as local topography, thermal updrafts due to local heating of the earth's surface, the distribution of high-pressure and low-pressure air masses, and storms and their associated turbulence. All of these factors can be predicted to some extent, but the reliability of the prediction decreases with both time and distance. For that reason, air-breathing missiles must be provided with means for correcting any deviation in course that might result from unpredicted winds. A ballistic missile may be subject to correction as it rises through the atmosphere. But it descends on its target at such a speed that the effect of wind is unlikely to produce a serious error.

A long-range missile using a navigational guidance system may use the direction of the center of the earth as a reference. It does so by using a pendulum, plum bob, or some similar device, to measure the direction of the gravitational force. But the measuring device is acted on by two forces: gravity, which tends to pull it toward the center of the earth; and centrifugal force, caused by the earth's rotation, acting at a right angle to the earth's axis. The direction indicated by the measuring device is that of apparent gravity—the resultant of the two forces. The motion of the missile itself will create additional forces that tend to disturb the gravity-measuring device. Any missile guidance system that uses a gravitational reference must compensate for these disturbing forces.

Some missile may use the strength or the direction of the earth's magnetic field as a reference for navigation. But both strength and direction of the field vary from point to point on the earth. In general, these variations have been measured and plotted. But at any given point on the earth, the magnetic field is subject to annual, monthly, and even daily variations. It is subject to non-periodic variations in "magnetic storms" that result from bursts of ions or electrons radiated from the sun. Most of these variations are predictable with reasonable accuracy, and can be taken into account in the missile guidance system.

The CORIOLIS FORCE must also be compensated for. It is caused by the earth's rotation, and tends to deflect a missile to the right in the northern hemisphere, and to the left in the southern hemisphere. As the earth turns on its axis, its surface moves toward the east at a rate determined by latitude. At the equator, the earth's surface is moving to the east with a speed of more than 1,000 mph; at the poles, its speed is zero.

Assume that a missile is launched directly northward in the northern hemisphere. At the instant of launching, it will be moving to the east at the same rate as the surface from which it is launched. But as it moves northward, it flies over points whose eastward velocity is less than its own. As a result it will be deflected eastward, or toward the right. Now imagine a missile fired southward in the northern hemisphere. It will fly over points whose eastward velocity is greater than its own. It will therefore be deflected westward (still to the right) with respect to the surface.

The amount of deviation produced by the coriolis force depends on the latitude, length, and direction of the missile flight. Since it can be accurately predicted, suitable corrections can be made by the missile guidance system.

CHAPTER 3

GUIDED MISSILE COMPONENTS

A. Introduction

3A1. General

This chapter is intended to provide an overall view of a guided missile and its various components. Most of the material in this chapter is covered in more detail elsewhere in this text. Airframes and control surfaces, for example, were treated in chapter 2. Propulsion systems, control systems, and guidance systems are each given one or more separate chapters. Their principal features will be briefly summarized here. War heads which are not covered elsewhere in this text, will be treated in some detail.

The principal components of a guided missile are:

WAR HEAD. The war head may be designed to inflict any of several possible kinds of damage on the enemy. The war head is the reason that the missile exists; the other components are intended merely to insure that the war head will reach its destination.

AIRFRAME. The airframe is the physical structure that carries the war head to the enemy, and contains the propulsion, guidance, and control systems

PROPULSION SYSTEM. This system provides the energy required to move the missile from the launcher to the target.

CONTROL SYSTEM. The control system has two functions. It keeps the missile in stable flight, and it translates the commands of the guidance system into motion of the control surfaces, or into some other means for modifying the missile trajectory.

GUIDANCE SYSTEM. This system determines whether or not the missile is on the course required to reach the target. If the missile is off course, the guidance system sends appropriate commands to the control system.

B. Airframe

3B1. General

The term AIRFRAME has the same meaning for guided missiles as it has for the conventional airplane. It serves as a vehicle to carry all the other parts of the missile, and it provides the aerodynamic characteristics required for successful flight. Research on airframes is a major part of our missile development effort. In the event of war or national emergency, the manufacture of missile airframes will probably assume the proportions of a major industry.

3B2. Body configuration

The Navy missiles described and illustrated in chapter 1 show the range of body configuration found in operational missiles. In general, the design of the airframe is determined by performance requirements. For example, Regulus 1 is strikingly similar in appearance to a jet fighter of similar performance, in the high subsonic speed range. Its wings, like those of carrier aircraft, may be folded. Before launching, the wings are extended and locked in place. The test version of Regulus has retractable landing gear. (Regulus differs from a conventional aircraft in that its wings depend only on angle of attack, rather than the Bernoulli effect, for lift).

Regulus II has some resemblance to a conventional aircraft, but its form has been greatly modified for supersonic speed. It is long and narrow as compared to Regulus I. Its nose is long and sharp, and its wings are severely swept back. Both versions of Regulus carry control surfaces similar in location and function to those of conventional aircraft.

Terrier, Sidewinder, and Talos are typical of a second class of airframe. In general, the airframe is a long, slender cylinder without wings. Its tail fins provide weathercock stability. A second set of fins, mounted near the center of the missile or forward of the center, provide additional stability. Control of the missile is accomplished by pivoting one or more pairs of fins, rather than by the use of conventional ailerons, rudders, and elevators. Note that, as in Terrier, the forward

fins may be mounted at 45° angles to the horizontal and vertical.

The nose shape is determined by other requirements. The Terrier nose is long and slender, because that shape has been found highly efficient at supersonic speeds. Sidewinder, although it travels at a comparable speed, has a hemispherical nose. This is necessary because of the infrared seeking device located immediately behind the nose surface; a surface of any other shape would transmit a distorted indication of the target position. The nose of Talos is relatively blunt; it contains the air intake for the ram-jet engine.

Talos is, in effect, a double-walled tube. Its central part is taken up by the ram-jet engine. All of its other components—war head, fuel tanks, guidance and control systems—are crowded within the space between the inner and outer walls. (In one model, one of these components is carried inside the central diffuser in the nose.) The central part of Terrier is taken up by a chamber filled with solid rocket propellant. The war head, fuze, and the major part of the guidance and control systems, are located forward of the fuel chamber. But a part of the guidance and control system is located in the double-walled cylinder that surrounds the exhaust duct at the after end of the missile. Electric cables and pneumatic lines to maintain communication between the two parts of the guidance system pass through covered channels along the outside of the missile.

Polaris, pictured in chapter 1, represents still a third type of missile body configuration. Note that there are no external control surfaces; any necessary changes in trajectory are accomplished by jet deflection. Note also that the nose is bluntly rounded. Because Polaris is an intermediate-range ballistic missile, its trajectory takes it far beyond the earth's atmosphere. It descends on its target at a steep angle, and at tremendous speed. As it re-enters the atmosphere, friction with the air generates a great deal of heat. The Polaris nose cone will probably become white-hot on re-entry. Its shape and construction have been determined by the requirements of this problem. The shape of the nose cone is designed to cause a minimum increase in temperature, and to distribute the temperature build-up uniformly over the nose cone, rather than allowing it to concentrate in a small area. The materials for the outer surface have been especially developed to resist high temperature. Suitable insulation must be provided between the outer skin of the nose cone and the internal components, to prevent damage to or premature detonation of the war head.

C. Propulsion Systems

3C1. General

Because chapter 4 is devoted to propulsion systems, they will be covered very briefly here. The powerplants of guided missiles have been referred to as "reaction engines." But strictly speaking, any engine designed to propel a vehicle is a reaction engine. All of them operate in accordance with Newton's third law, which states that for every action there is an equal and opposite reaction. For example, the force that the tires of a car apply to the road is opposed by an equal and opposite force and it is this reaction that drives the car forward. A propellant-driven aircraft operates by increasing the momentum of the air; the resulting reaction is applied to the propeller and its shaft, and, through a thrust bearing, to the airframe. As we have pointed out earlier, speed requirements make it impossible to use propeller-driven missiles. Because the speed of the propeller tip exceeds the speed of the airframe, the propeller tip enters the transonic zone while the aircraft speed is considerably below the speed of sound. In the transonic zone, the thrust developed by the propeller drops off rapidly, and a further increase in aircraft speed becomes impracticable. Therefore, all current guided missiles depend on some form of jet propulsion.

3C2. Types of jet propulsion systems

Popular terminology makes a distinction between jets and rockets: a jet takes in air from the atmosphere, and propels itself forward by increasing the momentum of the air; a rocket needs no air supply, since it carries

its own source of oxygen. But this is a rather arbitrary distinction. Both types of engine operate by expelling a stream of gas at high speed from a nozzle at the after end of the vehicle. For our purposes, a rocket can be considered as a type of jet engine.

The pulse-jet, which propelled the German V-1, was used by the Navy to propel an early missile that is now obsolete. No current missiles are driven by pulse-jets. Talos, as you know, is propelled by a ram-jet. The Navy uses turbo-jets for its Regulus I and II, and for the now obsolete Petrel. Terrier, Sidewinder, and Polaris are propelled by solid-fuel rockets. Current developments appear to indicate that, until the advent of atomic propulsion, most if not all of our future missiles will be powered by solid-fuel rockets.

The liquid-fuel rocket is used in the Air Force ICBM's, and in that application it has certain advantages. Liquid fuel provides more energy than an equivalent weight of solid fuel, and can maintain a high thrust for a relatively long time. And a liquid-fuel propulsion system can be shut down by radio command at any desired instant, whereas a solid-fuel system can not. But the liquid-fuel rocket must have a rather complex system of fuel and oxidizer lines and pumps, and it requires relatively elaborate equipment at the launching site. At present, a large missile propelled by a liquid-fuel rocket requires a lengthy "count-down" before firing. The last two factors make the liquid-fuel rocket impracticable for ship-launched missiles.

D. War Heads

3D1. General

The war head is the reason-for-being of any service guided missile; it may contain any of a large number of destructive agents. This versatility must not be confused with interchangeability, because the design of the missile and war head must be thoroughly integrated.

The guided missile fuze may be defined as that device which causes the war head to detonate in such a position that maximum damage will be inflicted on an average target. A fuze may be any of several types, such as impact, time, or proximity.

Guided missiles are precision-built weapons; they are expensive in manpower, materials, and money. The most accurate control and guidance systems will be of little value if the war head cannot produce enough lethal effect at the right time to destroy or at least cripple the target. The war head problem must be solved for each type of missile, to permit final crystalization of any integrated missile plan.

The ultimate aims and desires of weapon-makers have always been to strengthen the "arm" of the user. The rock in the hand of primitive man added strength and distance to the blows that he could deliver; the bow and arrow greatly multiplied man's effective striking distance; and the rifle and cannon have progressively increased the strength and range of his striking power. Guided missiles are a new means for lengthening the arm of the user. But the striking effect depends on the nature of the war head and on how accurately it can be delivered to the intended target. The war head of a guided missile is its payload, and justification for employment of the missile lies in its ability to deliver its payload to the target.

A guided missile may carry one or more war heads, and one or more fuzes. Missile war heads intended for use against ships or land targets present similar design problems to those of older weapons. Surface-to-air missiles present a somewhat different problem. The effective radius of damage from a high-explosive war head in the air depends on the type, shape, and size of the charge, and on the nature of the target itself.

The designer of the payload for any type of military weapon is faced with a number of variables, some of which are unpredictable. For example, in the design of an anti-aircraft missile, he must consider the following factors among others:

1. Altitude affects the lethal radius of a fragmentation war head; the fragments maintain a lethal velocity through a greater distance at high altitudes.

2. The relative velocity of target and missile has a direct bearing on the optimum angle of ejection of fragments. The designer must

determine the angle at which the greatest mass of fragments should be ejected. The timing sequence of fuze operation, as well as the guidance system of the missile, must function with great precision if the target is to be destroyed. The fuze must be both sensitive and fast to ensure success against high-speed aircraft or supersonic missiles.

3. The armor of the target, if any, influences the design specifications for fragment size and velocity. Fragments that are effective against conventional aircraft of today may be too light or too slow to penetrate the protective covering of the airplanes or missiles of the future.

The multiplicity of types of ground targets has led to the development of numerous types of lethal devices—from hand grenades to hydrogen bombs. A 500-pound bomb may be armor-piercing, semi-armor-piercing, or general-purpose. It may be equipped with an impact fuze, a time fuze, a proximity fuze, or a combination of these types.

The type of target is the most influential factor in war head design. A fragmentation-type war head might be effective against conventional aircraft, or against missiles of moderate speed. But a missile intended for use against a whole fleet of attacking bombers, or against a high-speed ballistic missile, would require an entirely different type of war head. Because of the wide variety in types of surface targets, it is necessary either to have missiles that can use several types of war heads interchangeably, or to develop a whole family of missiles for this application.

3D2. Types of war heads

The types of war heads that might be used with guided missiles include: external blast, fragmentation, shaped-charge, explosive-pellet, chemical, biological, and nuclear. (Other types of war heads will be discussed in a classified supplement to this text.)

BLAST-EFFECT WAR HEAD. The blast effect war head consists of a quantity of high-explosive material in a metallic case. The force of the explosion sets up a pressure wave in the air or other surrounding medium; the pressure wave causes damage to the target. This type of war head is most effective against underwater targets, because water is incompressible, and relatively dense. Torpedo war heads are of this type. Blast-effect war heads have been used successfully against small ground targets. They are considerably less effective against aerial targets because the density of the air, and therefore the severity of the shock wave, decreases with altitude.

FRAGMENTATION WAR HEAD. The fragmentation war head uses the force of a high-explosive charge to break up the war head casing into a number of fragments, and to propel them with enough velocity to destroy or damage the target. The size and velocity of the fragments, and the pattern in which they are dispersed, can be controlled by variation in the design and construction of the war head. The velocity of the fragments depends on the type and amount of explosive used, and on the ratio of explosive-to-fragment weight. The average size of fragments depends on the shape, size, and brittleness of the war head casing, and on the quantity and type of explosive. Greater uniformity in fragment size can be achieved by scoring or otherwise weakening the casing in a regular pattern, as shown in figure 3D1.

The damage produced by a fragmentation war head depends on the amount of metal available to form fragments, and on the amount of explosive available for breaking the casing and propelling the fragments. Aerial targets are more susceptible to damage by fragments if the war head explodes a short distance away, rather than in contact with the target. Against a partially protected surface target, a fragmentation war head is most effective when exploded in the air above the target, rather than on the ground. Figure 3D2 shows this effect. Fragments from the air burst strike the partially protected target and the entrenched personnel.

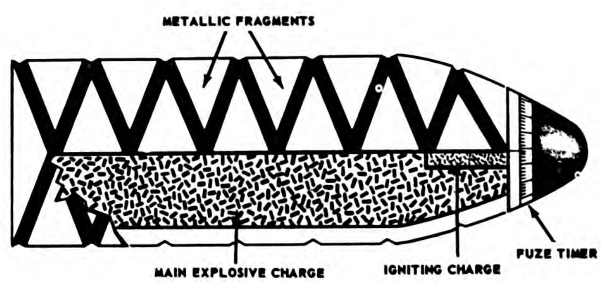


Figure 3D1.—Basic construction of a fragmentation war head.

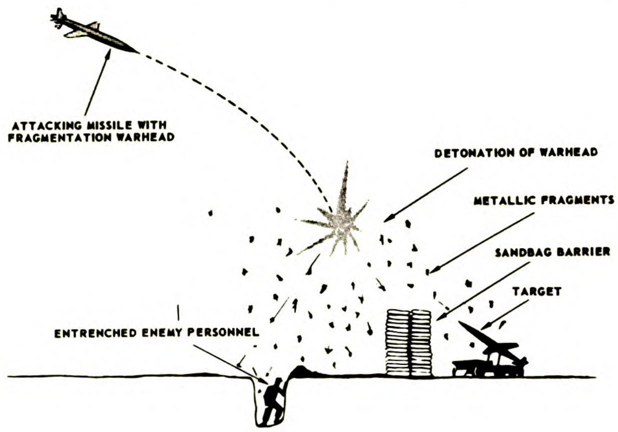


Figure 3D2.–Effect of fragmentation war head on surface targets.

SHAPED-CHARGE WAR HEAD. A shaped charge consists of a casing and a quantity of high explosive. The explosive is so shaped that the force of the blast it produces is largely concentrated in a single direction. As a result, a shaped charge has high penetrating power. It is widely used against armored surface targets. For example, the antitank bazooka rocket used during World War II and in Korea uses a shaped charge.

Figure 3D3 shows how the shape of the charge affects the penetrating ability of the blast. All three of the charges shown in the figure have the same weight of explosive. The flat charge at the left produces an explosive force rather evenly distributed over a given area of the target; this charge produces little penetration. The shallow-cone shape of the middle charge produces a greater concentration of the explosive force, and penetration of the target is deeper. The deep-cone shape at the right has concentrated the explosive force so as to penetrate the target armor. Metallic fragments of the armor can now reach the interior of the target, and do additional damage.

EXPLOSIVE-PELLET WAR HEAD. An explosive-pellet war head consists of a group of separately fuzed explosive pellets housed in a casing. The casing contains an additional quantity of explosive to eject the pellets from the main war head casing. The pellets themselves do not explode until they contact or penetrate the target. If the target is an aircraft or missile, maximum destruction can be accomplished when the pellets are detonated after penetrating the outer skin of the target. Each pellet contributes both blast effect and high-velocity metallic fragments when detonation occurs. (Because of high cost due to manufacturing difficulties, war heads of this type are rarely used.)

CHEMICAL WAR HEADS. A chemical war head is designed either to eject poisonous

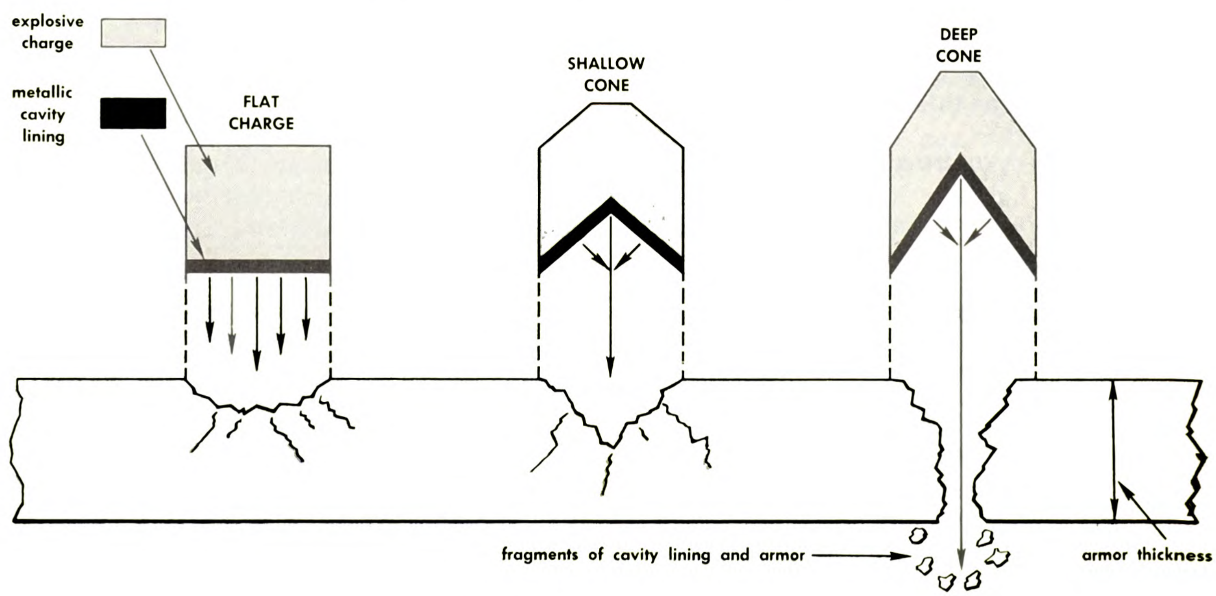


Figure 3D3.–Effects of various charge shapes.

substances and thus produce personnel casualties, or to destroy combustible targets by the use of incendiary materials. Although the use of poisonous gases in warfare appears to be obsolete, the possibility of their use remains as a threat. It is likely that quantities of poisonous war gases are included in the arsenal of every major power. Missile war heads can, of course, be designed to carry any type of poisonous gas.

Incendiary war heads contain chemicals that burn violently at high temperature, cover a large area when released, and are difficult to extinguish. They are used principally against surface targets, but may also be effective against aerial targets that contain combustible materials. Incendiary materials suitable for use in war heads include magnesium, jellied oil or gasoline, and phosphorous.

BIOLOGICAL WAR HEADS. A biological war head contains bacteria or other living organisms capable of causing sickness or death. The biological agent can be specifically chosen for use against personnel, livestock, or crops. Antipersonnel agents might be chosen to cause either temporary disability or death, depending on the objectives of the attacker. An explosive charge placed in a biological war head would ensure ejection and initial dispersion of the biological agents. Special attention must be given to the design and construction of biological war heads, in order that the bacteria or other agent will remain alive, and be carried to the target under the most favorable conditions.

NUCLEAR WAR HEADS. A number of current guided missiles have nuclear capability. Nuclear war heads are suitable for use against large surface targets, against fleets of bombers, and against intercontinental ballistic missiles. Nuclear weapons are discussed in detail in the second part of this text.

3D3. Fuzes

A fuze is a device that initiates the explosion of the main charge in an explosive weapon. In a guided missile the fuze may or may not be a physical part of the war head. In any case, it is essential to proper war head operation. A large variety of fuze types is available. The fuze type for a given application depends on characteristics of the target, the missile, and the war head. To insure the highest probability of lethal damage to the target, fuze design must be based on the location, vulnerability, speed, and physical structure of the target.

IMPACT FUZE. Impact fuzes are actuated by the inertial force that occurs when a missile strikes a target. Figure 3D4 is a schematic representation of an impact fuze. As shown in the left-hand diagram, a charge of sensitive explosive is contained in the forward end of the fuze; a movable plunger is mounted in the after end, where it is held in place by a spring or other suitable device.

During the flight of the missile, the plunger remains in the after end of the fuze. When the missile strikes the target, it decelerates suddenly, and the inertia of the plunger carries it

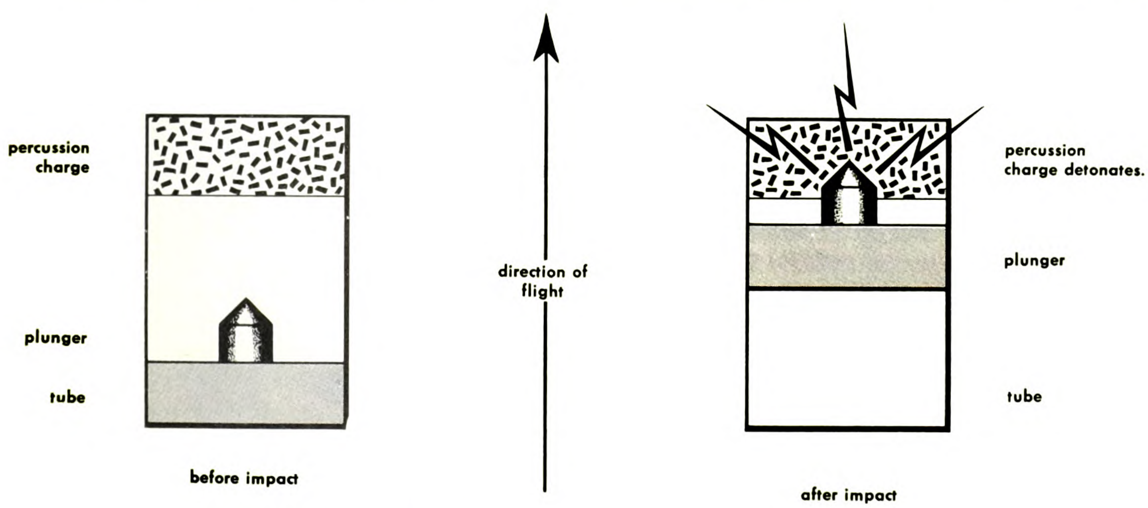


Figure 3D4.—Impact fuze before and after impact.

forward. As shown in the right-hand diagram, figure 3D4, the plunger strikes the shock-sensitive explosive and detonates it. The fuze charge in turn detonates the main bursting charge of the war head. A time delay element is sometimes used in conjunction with an impact fuze, so that the war head can penetrate the target before detonation.

An impact fuze may be used in conjunction with a fuze of another type, such as a proximity fuze. If the proximity fuze fails to operate as the missile approaches the target, the impact fuze will still function on contact.

TIME-DELAY FUZE. Time delay fuzes are used in some types of gun projectiles. This fuze is designed to detonate the war head when a predetermined time has elapsed after firing or launching. One type of time delay element consists of a burning powder train; another uses a clock-like mechanism. In either type, the time interval can not be changed after launching. For that reason, time-delay fuzes are unlikely to be used in guided missile war heads.

PROXIMITY FUZES. Proximity fuzes are often called VT (variable time) fuzes. They are actuated by some characteristic feature of the target or the target area. Several types of proximity fuze are possible; for example, photo-electric, acoustic, pressure, radio, or electrostatic. Each of these types could be preset to function when the intensity of the target characteristic to which it is sensitive reaches a certain magnitude.

Proximity fuzes are designed so that the war head burst pattern will occur at the most effective time and location relative to the target. Designing the fuze to produce an optimum burst pattern is not easy, since the most desirable pattern depends largely on the relative speed of missile and target. If targets with widely varying speeds are to be attacked, it might be possible to adjust the fuze sensitivity for the speed of the individual target, as predicted by a computer. Proximity fuzes activate the war head detonating system after integrating two factors: the distance to the target, and the rate at which the range is closing.

Since a proximity fuze operates on the basis of information received from the target, it is subject to jamming by false information. This is one of the important problems in proximity fuze design. The fuzes are designed for the

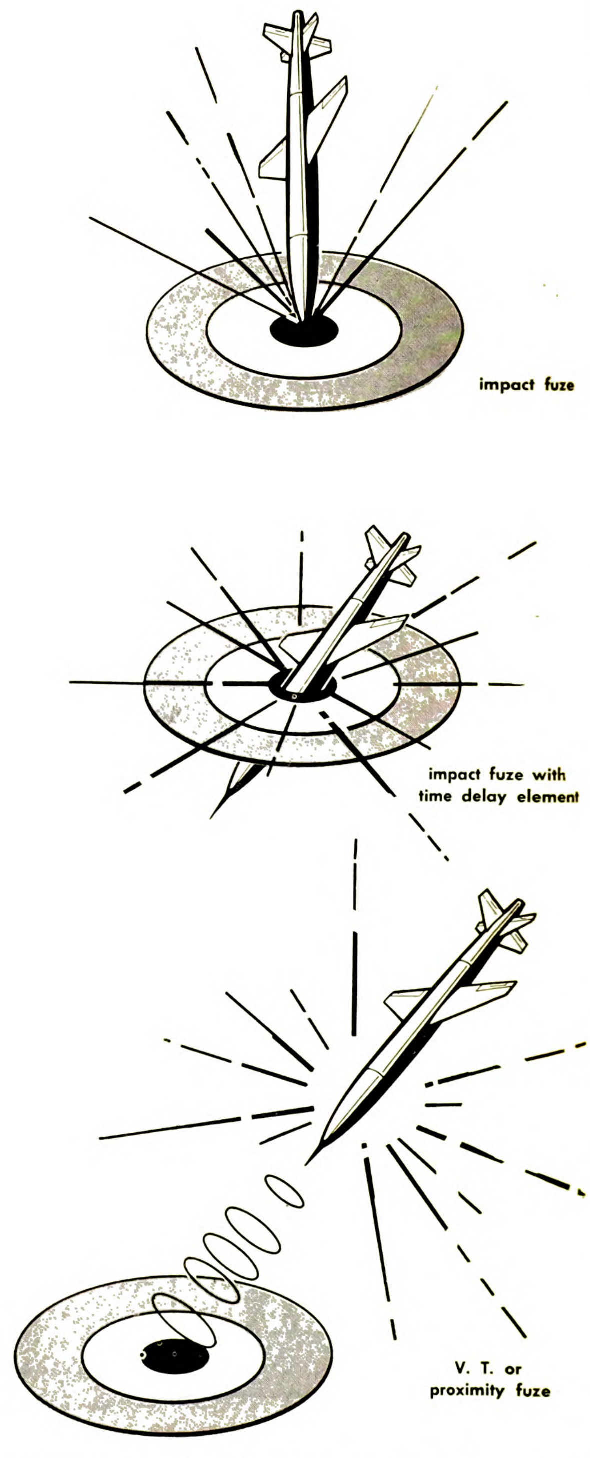


Figure 3D5.—Influence of fuze on point of war head detonation.

maximum resistance to countermeasures consistent with other requirements. If the fuze is made inoperative by jamming, the missile can not damage the target unless it scores a direct hit. A more serious possibility is that jamming, instead of making the fuze inoperable, might cause premature detonation of the war head before the missile approached the target within lethal range.

Although any of the effects listed above—photoelectric, acoustic, pressure, radio, or electrostatic—can be used as the basis for proximity fuze action, and although all of them have been used at least experimentally, it has been found in practice that the radio proximity fuze is more effective than any of the others. The radio proximity fuze is the only type used by the Navy. This fuze transmits high-frequency radio waves, which are reflected from the target as the missile approaches it. Because of the relative motion of missile and target, the reflected signal, as received at the missile, is of a higher frequency than the transmitted signal. The two signals, when mixed, will generate a doppler frequency, the amplitude of which is a function of target distance. When this amplitude reaches a predetermined level, the fuze functions and detonates the war head.

FUZE POSITION IN WAR HEAD. In general, fuzes may be classified as NOSE FUZES, located in the nose of the war head, or BASE FUZES, located at its after end. As previously stated, the fuze or combination of fuzes to be used, and their location in the war head, depend on the mission at hand and the effect desired.

WAR HEAD DETONATION POINTS. Figure 3D5 shows the effect of fuze type on the point at which the war head detonates. The war head of the missile in the upper drawing is provided with an impact fuze, and the war head detonates at the instant the missile strikes the target. The missile in the middle drawing has an impact fuze provided with a time-delay element. The time delay allows the war head to penetrate the target before detonation. In the lower drawing, the missile has a proximity fuze, which has been actuated by some characteristic of the target, causing war head detonation at a predetermined distance from the target.

E. Telemetering Systems

A missile-telemetering system consists of measuring devices and radio transmitting equipment, the purpose of which is to measure the performance of various missile components throughout the missile flight, and to transmit this information to recording instruments on the ground.

During the early stages in the design and development of a missile, electronic analog computers are used to predict the performance of proposed missile components. In later stages of development, missile components and systems must be tested in actual flight. The test versions of Regulus are designed for intact recovery after test flights, and recording equipment to indicate the second-by-second performance of missile components can be carried within the missile itself. But most missiles are non-recoverable. Telemetering equipment is therefore essential to an evaluation of component and system performance, and to indicate the cause of component failure. Telemetering data thus provides the basis for improved designs. Although telemetering is most useful during the development stages before a missile becomes operational, it should be remembered that missile designs are constantly being improved. Telemetering equipment will play a useful part in practice firing of some operational missiles. It seems likely that, even when launched against an enemy in time of war, the very large missiles will be provided with some form of telemetering equipment.

TELEMETRY is a word of Greek origin meaning measurement from a distance. Telemetry includes (1) conversion of quantities to be studied into electric signals, (2) transmission of these signals over a radio link, (3) reception of the signals, and (4) presentation of the quantities in the form of indications and permanent recordings. The recordings are retained for detailed analysis. This telemetering permits the measurement and study of missile component performance from a remote point. Photographic or other recording made in the missile itself (as in test flights of Regulus) are not considered telemetering, because

there is no great distance between the measuring and the recording instruments.

A simple telemetering system might measure only "yes-no" information, such as whether or not the fuze is armed at any given instant. This type of system tells an observer when an event has taken place. A usual method is to change an audio modulation frequency each time an event takes place. The frequency change gives evidence that the transmitter was working both before and after each successive event. In such a transmitter no rigid demands are made on the stability of the audio frequency, or upon its waveform.

An instrument panel observed through a television camera constitutes a form of telemetering with a large number of channels, in which quantitative information is made immediately available for observation and recording. Radiosondes suspended from weather balloons provide weather information by sampling the readings of various meteorological instruments in sequence. Resistance values are caused to vary with humidity, temperature, etc. This variation in turn causes modulation of the transmitter carrier frequency.

Telemetering in one form or another has been used in radio-controlled and other airplanes for a number of years. Guided missiles present their own peculiar problems, caused by limited space, high launching acceleration, high speed, and the varied and numerous measurements required.

A great deal of information is needed during the various stages of a missile test or development program, on such subjects as launching performance, flight data, and operation of the control and guidance systems. Data measured by the telemetering systems of guided missiles include (1) changes of attitude in roll, pitch, and yaw; (2) flight data such as air speed and altitude; (3) missile acceleration during launching or maneuvering; (4) ambient conditions of temperature, humidity, and pressure; (5) structural information such as vibration and strain; (6) control functions, such as operation of the control receiver, autopilot operation, servo operation, displacements of control surfaces, and operation of the homing or other target-seeking equipment; (7) propulsion information, including fuel flow and thrust; (8) ordnance functions such as fuze arming time; (9) upper-air research data; (10) the performance of the electric, hydraulic, and pneumatic systems; and (11) information on the performance of the telemetering equipment itself, including reference voltages for calibration and time marks, to permit synchronizing recordings as received by several different receivers located along the flight path.

Many of these measurements are interrelated. Some of them require a high order of time resolution, especially as the speed of the missile increases. For others, a few samplings per second are adequate. A telemetering system must be capable of transmitting large amounts of varied data each second. With so much information to be handled, a multi-channel system is plainly indicated, because a single commutated channel would not give sufficient time resolution.

The nature of the telemetering installation is determined by the requirements of the particular test, and the exact functions to be telemetered for each flight must be carefully chosen. For example, a small number of functions may be studied with great precision, rather than a larger number of functions on a time-sharing basis. Such a selection might also result in a saving in the time required for missile instrumentation. Because most missiles are fired only once, the telemetering must be reliable or a sizable expenditure of time and money will be wasted. It follows, therefore, that accuracy, stability, and simplicity are imperative. Because of these requirements, telemetering personnel check their calibration work just prior to launching. Launching subjects the missile-borne telemetering equipment to severe conditions of acceleration, vibration, and sometimes condensation. For example, when a missile is launched at high altitude from a parent plane, its parts may be cold. When the missile reaches a lower altitude, the condensation that takes place may impair operation of the telemetering equipment.

The missile may roll, or it may be thrown into a climb or dive, and through all these gyrations the telemetering equipment must continue to function. A directional antenna may cause the signal to be lost entirely, along with valuable information, at a critical time; such an antenna requires a number of data-receiving stations to ensure continuous reception. The pattern of the antenna on the missile should be such that reception is not impaired

by changes in missile attitude. The antenna should be designed for minimum aerodynamic drag; with supersonic missiles, this requirement is particularly important. Nose probes or an insulated section of the missile nose are sometimes used as radiating surfaces. In some missiles, a part of the airframe itself is excited by a feedline and serves as a transmitting antenna.

As in any system of measurement, the telemetering system should neither impair the operation of the equipment it monitors, nor exert an undue influence on the quantities it measures. In small missiles, the distribution of telemetering instruments must be so arranged that the center of gravity remains undisturbed. Telemetering equipment must be appropriately packaged to fit the particular requirements of the missile airframe—generally by utilizing a number of small components properly located with respect to sources of heat, vibration, etc.

Data transmitted from the missile may be observed on instruments as the flight progresses, and simultaneously recorded on film or magnetic tape. Suitable decoding and computing equipment are used to facilitate the work of data reduction and analysis.

CHAPTER 4
MISSILE PROPULSION SYSTEMS

A. Introduction

4A1. General

Until the start of World War II, the reciprocating engine-propeller combination was considered satisfactory for the propulsion of aircraft. We have already explained the speed limitations of propeller-driven craft. As the speed of the propeller approaches the speed of sound, shock waves form and limit the development of thrust. This condition requires the use of extremely large engines to produce any further increase in speed. Research in the design of propellers may make it possible to overcome some of their limitations. But, at present some form of jet propulsion is required for high subsonic and supersonic speeds.

Guided missiles must travel at high speeds to lessen the probability of interception and destruction by enemy countermeasures. Although a few high-subsonic missiles, such as Regulus I and Snark, are still operational for use against surface targets, the increasing efficiency of countermeasures tends to make all subsonic missiles obsolete. Missiles intended for use against high-speed enemy missiles and manned aircraft must be capable of high speeds. All air-to-air and surface-to-air missiles now operational fly at supersonic velocities. Naturally, all guided missiles now operational depend on some form of jet engine for propulsion.

As we have explained in earlier chapters, jet propulsion is a means of locomotion brought about by the momentum of matter expelled from the after end of the propelled vehicle. This momentum is gained by the combustion of either a solid or a liquid fuel. Compared to reciprocating engines, jet propulsion systems are simple in construction. The basic components of a jet engine are a combustion chamber and an exhaust nozzle. Some systems require accessory components such as pumps, injectors, turbines, and ignition systems.

4A2. Classification of jet systems

Jet propulsion systems used in guided missiles may be divided into two types: ducted propulsion systems and rockets.

Missiles using a ducted propulsion system fly through the air: they are incapable of operating in a vacuum. The missile takes in a quantity of air at its forward end, increases its momentum by heating it, and produces thrust by permitting the heated air and fuel combustion products to expand through an exhaust nozzle. This process may be broken down into the following steps: air is taken in and compressed; liquid fuel is injected into the compressed air; the mixture is burned; and the resulting hot gases are expelled through a nozzle. The air may be compressed in any of several ways. In a turbo-jet engine, air is compressed by a rotary compressor, which in turn is operated by a turbine located in the path of the exhaust gases and mounted on the same shaft as the compressor. (A turbo-prop engine, now used in some manned aircraft but not in guided missiles, makes use of a propeller mounted at the forward end of the compressor turbine shaft.) In a pure duct system, such as the ram-jet, air is compressed by the forward motion of the missile through it. The now obsolete pulse-jet also depends on forward motion; it differs from the ram-jet in that combustion is intermittent, rather than continuous.

Rockets do not depend on air intake for their operation, and are therefore capable of traveling beyond the atmosphere. A rocket engine carries with it all the materials required for its operation. These materials usually consist of a fuel and an oxidizer. The oxidizer is a substance capable of releasing all the oxygen required for burning the fuel.

B. Principles of Jet Propulsion

4B1. Basic laws and formulas

In this article we will show, with the help of some elementary mathematics, how a jet-propulsion system develops the thrust required to propel a guided missile. All jet-propulsion systems are based on the principles expressed in Newton's second and third

laws of motion. Newton's second law says that when a body is acted on by an unbalanced force, the body will accelerate in the direction of the applied force. The acceleration produced is directly proportional to the magnitude of the force, and inversely proportional to the mass of the body. This relation can be expressed as a formula:

$$F = Ma$$

or, force equals mass times acceleration. In this formula, force is expressed in pounds, acceleration in feet per second per second, and mass in SLUGS. The weight of any given mass varies, depending on the force of gravity. Gravity varies with the distance from the earth's center. The relation between weight and mass can be expressed in the formula:

$$M = \frac{W}{g}$$

in which M is the mass in slugs, W the weight in pounds, and g the acceleration due to gravity in feet per second per second (approximately 32.2 ft/sec^2 at sea level).

Acceleration is the rate of change of velocity. This is expressed in the formula

$$a = \frac{v_2 - v_1}{t}$$

where v_1 is the initial velocity of a mass, v_2 its final velocity, and t the time during which this change of velocity occurs. If we substitute the above value of acceleration in the original formula, $F = Ma$, we get

$$F = \frac{Mv_2 - Mv_1}{t}.$$

Since Mv is momentum, the above formula shows that the thrust produced by a jet engine is equal to the rate of change of momentum of its working fluid. We can write the above formula as follows:

$$F = m\,(v_2 - v_1)$$

where m represents M/t, and is called the mass rate of flow of the working fluid in slugs per second.

In the original equation, $F = Ma$, we can substitute the equivalent weight for mass, and get

$$F = \frac{W_a}{g}.$$

When we apply this formula to a jet propulsion system, F is the unbalanced force that accelerates the working fluid through the exhaust nozzle, and a is the acceleration of the fluid in feet per second per second. In accordance with Newton's third law of motion, the forward thrust developed by the jet propulsion system is equal and opposite to the unbalanced force applied to its working fluid.

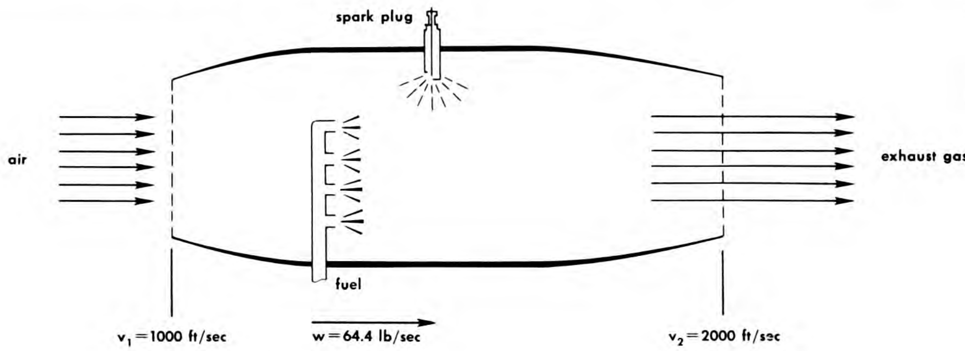
Now, let W equal the total weight of working fluid that flows through a missile propulsion system during the time the system is producing thrust, and let t equal the total time during which the system develops thrust. Then W/t is the weight rate of flow of working fluid, in pounds per second. Letting $w = W/t$, we can now write a formula for the thrust developed by a jet propulsion system:

$$T = \frac{w}{g}\,(v_2 - v_1)$$

where T is the thrust in pounds; w is the weight rate of flow of the working fluid, in pounds per second; v_1 is the initial (intake) velocity of the working fluid; v_2 is the final (exhaust) velocity of the fluid; and g is the acceleration due to gravity. This equation gives the thrust applied to expel the working fluid from the exhaust nozzle of the engine. And, in accordance with Newton's third law of motion, the same equation also expresses the forward thrust developed by the propulsion system to propel the missile.

Figure 4B1 represents a jet engine which is taking in air at its forward end at a speed of 1,000 feet per second. The burning fuel within the engine heats the air and increases its speed to 2,000 feet per second. If we assume that the working fluid flows through the engine at the rate of 64.4 pounds per second, application of the thrust formula shows that this engine is developing a thrust of 2,000 pounds.

Note that the thrust developed by an engine is always expressed in POUNDS OF FORCE, not in terms of work or horsepower. A jet engine that is fired in a test stand does not



$$\text{thrust} = \frac{w}{g}(V_2 - V_1)$$

$$\text{thrust} = \frac{64.4 \text{ lb/sec}}{32.2 \text{ ft/sec}^2}(2000 \text{ ft/sec} - 1000 \text{ ft/sec})$$

$$\text{thrust} = 2000 \text{ lbs.}$$

Figure 4B1.—Practical example of Newton's second law of motion.

move. It therefore does no work, and consequently develops no horsepower, although it may exert its maximum thrust. For a missile in actual flight, it is possible to calculate the horsepower developed by the propulsion system from the formula:

$$\text{Horsepower} = \frac{VT}{375}$$

where V is the missile velocity in miles per hour, T is thrust in pounds, and 375 is a constant having the dimensions of mile-pounds per hour. For example, assume that a missile traveling at 3750 mph has 56,000 pounds of thrust. The above equation shows that the engine is developing 560,000 horsepower:

$$\frac{3750 \times 56{,}000}{375} = 560{,}000 \text{ hp}$$

Although it is possible to calculate the horsepower developed by the propulsion system of a missile in flight, the student should remember that jet-propulsion engines are always rated in terms of pounds of thrust, rather than in horsepower.

A rocket engine takes in no air from the atmosphere; its working fluid consists of the combustion gases resulting from burning fuel. Since the rocket carries its own supply of oxygen as well as its fuel supply, the initial velocity of the working fluid, relative to the missile, is zero. Thus, the formula for the thrust developed by a rocket engine reduces to

$$T = \frac{W}{g} v_e$$

where w is the rate of fuel and oxidizer consumption in pounds per second, and v_e is the exhaust velocity of the gases. But the above formula expresses only the thrust due to momentum of the working fluid. If the pressure of the working fluid, after it leaves the exhaust nozzle, is greater than the pressure outside the missile, the actual thrust is less than that given by the above formula. It is obvious that if the gases that have left the missile are at a higher pressure than the surrounding atmosphere or space, these gases are capable of doing work. That work, which might have been used to propel the missile, will be wasted. A more accurate formula for rocket thrust is

$$T = \frac{W}{g} V_e + (P_a - P_e) A_e$$

in which P_a is the pressure of the surrounding atmosphere (or space), P_e is the pressure of the exhaust jet, and A_e is the cross-sectional area of the exhaust jet. If the exhaust nozzle can be so designed that it decreases the pressure of the exhaust jet to that of the surrounding space, the pressure term in the above equation becomes zero. This condition represents the maximum thrust available for any given propellant and chamber pressure. Although this condition cannot be fully attained

in actual practice, well-designed nozzles make it possible to approach it closely.

It is a common misconception that jet engines operate by pushing against the surrounding air. Ducted jets depend on air as a working fluid, but they do not need air for the exhaust to push against. Rockets require no air. Air acts only to impede the motion of a rocket, first by drag, and second by hindering the high-speed ejection of the exhaust gases. Thus rockets operate more efficiently in a total vacuum than they do in the atmosphere.

4B2. Propellants

The fuels and oxidizers used to power a jet engine are called propellants. The chemical reaction between fuel and oxidizer in the combustion chamber of a jet engine produces large quantities of high-pressure high-temperature gases. When these gases are channeled through an exhaust nozzle, a large part of the heat energy they contain is converted into kinetic energy to propel the missile. When you read of an engine that can travel faster than a gun projectile, operate in a vacuum, deliver a great deal more energy than a reciprocating engine, and do so with few or no moving parts, you may get the idea that some very complex chemical mixture is used as the propellant. This is not so. Jet-propulsion engines can operate on such fuels as kerosene, gasoline, alcohol, gunpowder, and coal dust.

With regard to their physical state, propellants may be either solids, liquids, gases, or various combinations of these. However, gases are rarely used as missile propellants, for two reasons. First, liquids or solids have a higher density than most gases, even when the latter are highly compressed; thus a larger quantity of solid or liquid propellant can be carried in a given space. Second, a greater energy transformation results when a substance goes from solid or liquid to gas than results when a gas is merely accelerated to a higher velocity.

Several means have been worked out for rating, or comparing, various propellants. For example, they may be compared on the basis of TOTAL IMPULSE. Total impulse is the product of the thrust in pounds and the burning time in seconds. Solid propellants are often rated on the basis of SPECIFIC IMPULSE, or the amount of impulse per pound.

The specific impulse of a propellant, in pound-seconds per pound, is equal to the total impulse divided by the weight of the propellant. Liquid propellants are often compared on the basis of SPECIFIC THRUST. This value is similar to specific impulse, but is derived in a slightly different way. Specific thrust is defined as the thrust that would be produced by a given liquid propellant if it were consumed at the rate of one pound per second. It is equal to the total thrust, in pounds, divided by the weight rate of flow in pounds per second, and is usually expressed in SECONDS.

SPECIFIC PROPELLANT CONSUMPTION is the reciprocal of specific thrust; it is the rate of propellant flow, in pounds per second, required to produce one pound of thrust. MIXTURE RATIO designates the relative quantities of oxidizer and fuel used in a given propellant combination. It is equal to the weight of oxidizer flow divided by the rate of fuel flow. SOLID PROPELLANTS are of two types. One of these consists of a fuel, such as a hydrocarbon, mixed with a chemical capable of releasing large quantities of oxygen, such as a chlorate or a nitrate. A second type consists of a compound that releases large quantities of gases and heat when it decomposes, such as nitrocellulose. Of course it is possible to combine the two types in a single propellant mixture. The ingredients of a solid propellant are mixed so as to produce a solid of the desired chemical and physical characteristics. The finished product is called a GRAIN or STICK. A CHARGE may be made up of one or more grains.

An ideal solid propellant would have all of the following characteristics: high specific impulse; manufactured from easily obtainable substances; safe and easy to handle; easily stored; stable to shock and temperature changes; ignites and burns uniformly; maintains constant burning surface; nonhygroscopic (will not absorb water vapor); smokeless; and flashless. It is doubtful if a single propellant having all of these qualities will ever be developed. Some of these characteristics are obtained at the expense of others, depending on the performance desired.

While solid propellants are stored within the combustion chamber of the propulsion system, liquid propellants are stored in tanks, and INJECTED into the combustion chamber. In general, liquid propellants provide a longer

burning time than solid propellants. They have a further advantage in that combustion can be stopped and started at will by controlling the propellant flow.

When oxygen or an oxygen-rich chemical is used as an oxidizer, the best liquid fuels appear to be those rich in both carbon and hydrogen. Examples are ethyl alcohol and aniline.

In addition to the fuel and oxidizer, a liquid propellant may also contain a catalytic agent to increase the speed of the reaction. Inert additives, which do not take part in the chemical reaction, are sometimes combined with liquid fuels. An example is water, which is often added when alcohol is used as a fuel. Although such additives add no energy to the system, they contribute to a higher thrust by increasing the rate of mass flow through the system.

An ideal liquid propellant would have all of the following characteristics: easily manufactured from available raw materials; high heat of combustion per unit weight of mixture, to give a high chamber temperature; low molecular weight of the reaction products; low freezing point; high specific gravity; low toxicity and corrosiveness; low vapor pressure; and stability in storage. As with solid propellants, it is unlikely that all of these characteristics will ever be combined in a single fuel.

4B3. Components of jet-propulsion systems

The principal parts of any jet-propulsion system are the combustion chamber and the exhaust nozzle. Liquid-fuel systems require additional parts, such as injectors, pumps, and ignition systems.

The COMBUSTION CHAMBER is the enclosure within which the fuel is burned, and energy changed from potential to kinetic. The chamber is usually a cylinder, although it may sometimes be a sphere. Its length and diameter must be such as to produce a chamber volume most suitable for complete and stable combustion. The chamber length and the nozzle EXIT DIAMETER are determined by the propellants to be used. Both must be designed to produce the optimum gas velocity and pressure at the nozzle exit.

The INJECTOR is similar in function to the carburetor in a reciprocating engine. It vaporizes and mixes the fuel and oxidizer in the proper proportions for efficient burning.

Figure 4B2 shows schematic sketches of three types of injector. In the multiple-hole impingement type, oxidizer and fuel are injected through an arrangement of separate holes in such a way that the jet-like streams intersect each other at some predetermined point, where the fuel and oxidizer mix and break up into vapor-like droplets. A spray injector has oxidizer and fuel holes arranged in circles, so as to produce conical or cylindrical spray patterns that intersect within the chamber. The nonimpinging injector, shown in the lower sketch in figure 4B2, is one in which the oxidizer and fuel do not impinge at any specific point, but are mixed by the turbulence within the chamber.

Unless the fuel and oxidizer form a combination that ignites spontaneously, a separate IGNITION SYSTEM must be provided to initiate the reaction. The igniter must be located within the combustion chamber at a point where it will receive a satisfactory starting mixture that ignites readily. If either fuel or oxidizer accumulates excessively in the chamber before ignition begins, an uncontrolled explosion may result. In some systems, ignition is brought about by a SPARK PLUG similar to those used in reciprocating engines. A POWDER-CHARGE ignition system is often used for solid-fuel rockets. It consists of a powder squib which can be ignited electrically from a safe distance; it burns for a short time, with a flame hot enough to ignite the main propellant charge. A catalytic ignition system uses a solid or liquid catalytic agent that brings about chemical decomposition of the propellant.

An EXHAUST NOZZLE is a nonuniform chamber through which the gases generated in the combustion chamber flow to the outside. Its most important areas are the cross sections at the mouth, throat, and exit. These areas are identified in figure 4B3a. The function of the nozzle is to increase the velocity of the gases. Under conditions of steady flow, the weight of gas that passes any cross section in unit time is constant. (This is in accordance with Bernoulli's theorem). Thus, in subsonic flow, the velocity of the gases will increase at any point where the cross section

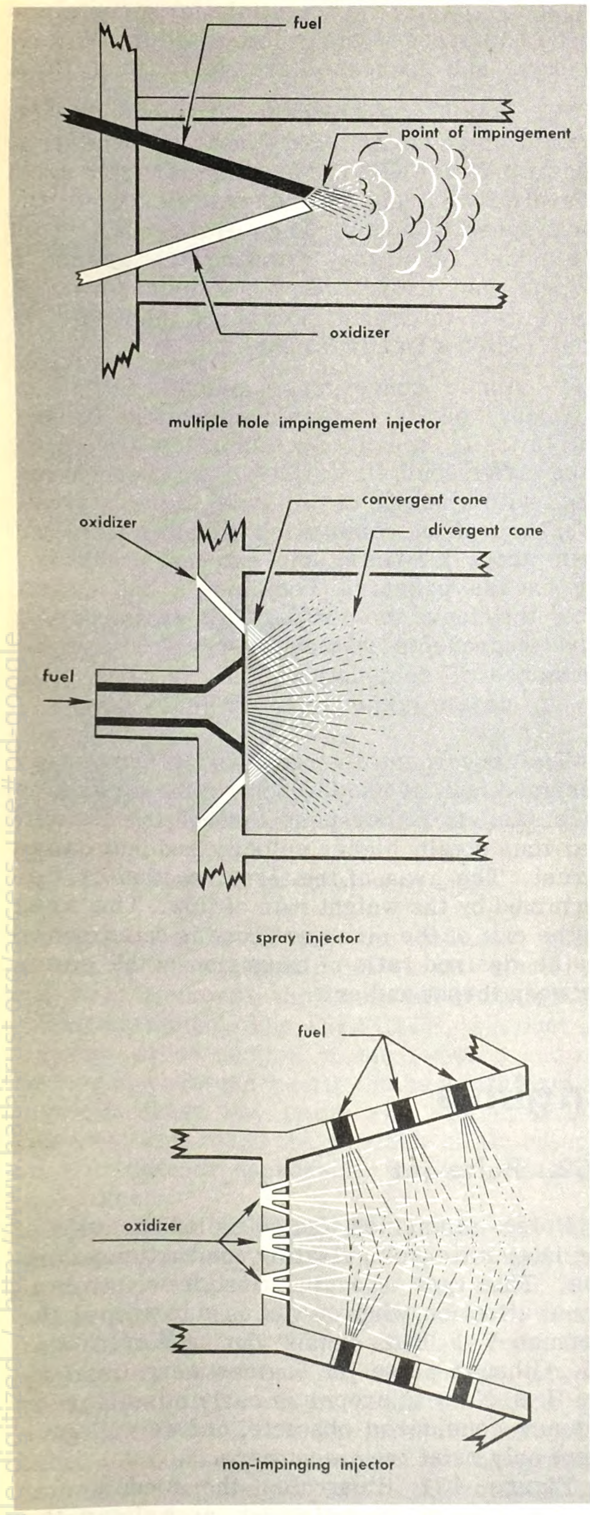


Figure 4B2.—Types of injectors.

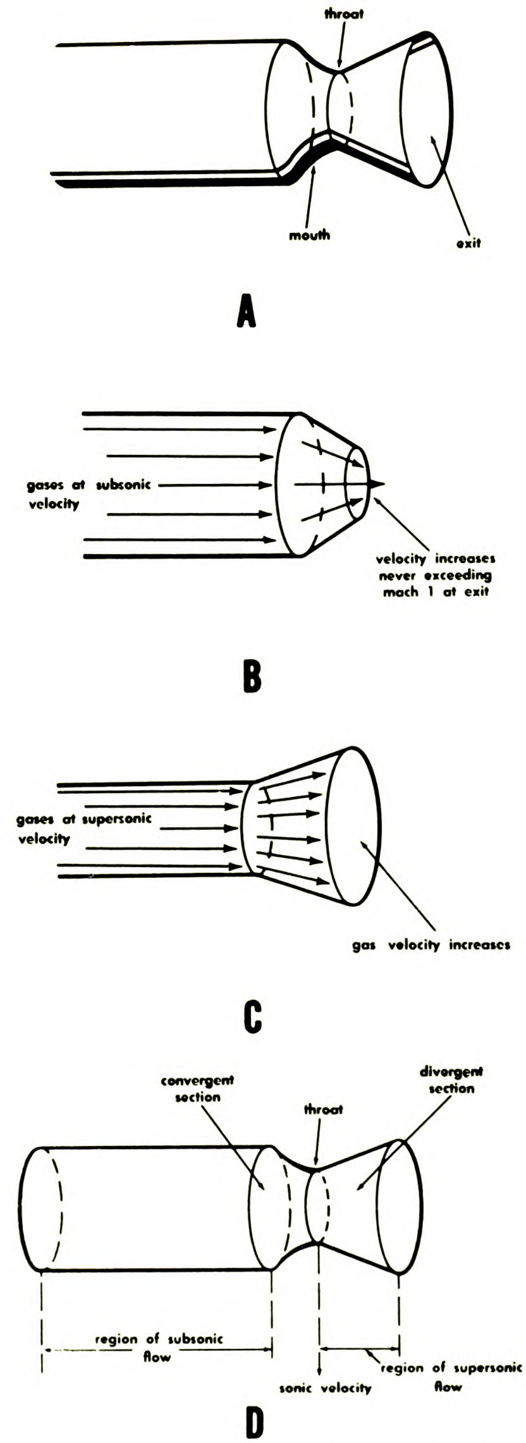


Figure 4B3.—a. Location of nozzle components; b. subsonic flow through a convergent nozzle; c. supersonic flow through a divergent nozzle; d. convergent-divergent, or DeLaval nozzle.

is constricted, provided the weight ratio of flow remains constant. Where the cross section becomes wider, the gas velocity will decrease. This relation of cross section to velocity always holds for subsonic flow.

Figure 4B3b shows a simple convergent nozzle. The speed of gases entering such a nozzle will increase. The greater the convergence, the greater the increase in speed, up to the local speed of sound. (When we refer to the local speed of sound at some point in the propulsion system, we mean the speed of sound that corresponds to the temperature and pressure at that specific point.) But, in a simple convergent nozzle, no further increase in speed will take place beyond Mach 1. The behavior of gases at supersonic speed differs considerably from that of gases at subsonic speed. For example, if gases at supersonic speed enter the convergent nozzle shown in figure 4B3b, they will SLOW DOWN.

Figure 4B3c shows a simple divergent nozzle. When gases enter such a nozzle at subsonic speeds, they slow down. But, when gases at supersonic speed enter a divergent nozzle, their speed is further increased. The decrease in speed in subsonic flow is in accordance with Bernoulli's theorem. Since the cross section increases and the weight-rate of flow remains constant, the velocity must decrease with a proportionate increase in pressure. But gases in supersonic flow are in a state of compression. When gases in supersonic flow enter a divergent nozzle, they expand. A part of the potential energy contained in the compressed gas is converted into kinetic energy, and increases the velocity of flow.

To obtain a supersonic exhaust velocity, most rocket motors use a nozzle of the type shown in figure 4B3d. The exhaust nozzle first converges to bring the subsonic flow up to the local speed of sound. Then at a certain point the nozzle diverges, allowing the gases to expand and produce supersonic flow. A convergent-divergent nozzle of this type is often called a DeLaval nozzle.

A simple convergent nozzle is the most efficient type for certain combinations of fuel and missile speed. Such nozzles are often used on subsonic turbo-jets. It has been found that, with a nozzle of this type, if the internal pressure of the combustion chamber is more than about 1.7 times the external pressure, an excess pressure remains in the gases after they leave the nozzle. This excess pressure represents wasted energy. The performance of combustion systems using this type of nozzle is therefore limited.

The convergent-divergent nozzle, if properly designed, can be used to control the expansion of gases after they pass through the throat, and thus obtain higher velocity and increased thrust. The area of the throat section is determined by the weight rate of flow. The area at the exit of the divergent cone is determined by the desired ratio of expansion of the gases between throat and exit.

C. Air Jet Engines

4C1. General

Any jet-propelled system that obtains oxygen from the surrounding atmosphere to support the combustion of its fuel is an air-jet engine. Pulse-jets, ram-jets, turbo-jets, and turbo-props are all of this type, although the latter are not used in guided missiles. Obviously, the operation of these engines is limited by the amount of oxygen available, and they can operate only at altitudes where the oxygen content of the air is adequate. The upper limit of operation depends on the type and design of the particular engine.

4C2. Pulse-jet

Pulse-jet engines are so called because of the intermittent or pulsating combustion process. This type of engine first drew international attention when it was used to propel the German V-1 "buzz bomb" during World War II. Although pulse-jet engines were used by the U. S. Navy to propel an early missile, they are now considered obsolete, and we will give them only brief treatment here.

Figure 4C1 illustrates the fundamental construction of the pulse-jet, as well as the stages of its combustion cycle. The principal

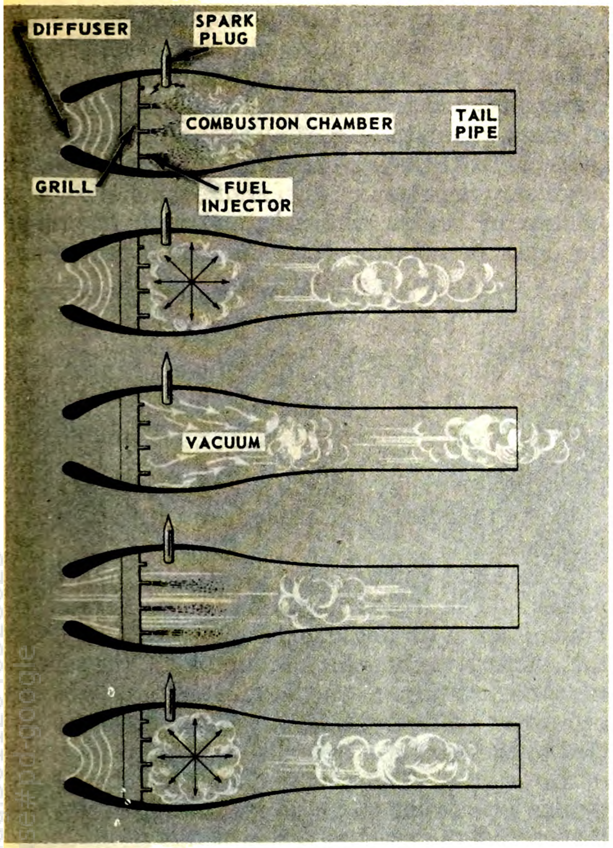


Figure 4C1.–Stages of pulse-jet engine.

parts of a pulse-jet are the diffuser, grill assembly (containing air valves, air injectors, and fuel injectors), the combustion chamber, and the tail pipe. The DIFFUSER is a duct of varying cross section at the forward end of the engine, between the air intake and the grill. Between these two points the diameter increases; as a result the velocity of air entering the diffuser decreases, and its pressure increases.

The GRILL ASSEMBLY carries the fuel injectors, injectors for starting air, and the air-intake "flapper" valves. The latter are spring loaded, and are normally closed, so as to completely block off the diffuser from the combustion chamber. As the engine moves through the air, ram-air pressure builds up in the diffuser. When this pressure exceeds that of the combustion chamber and the spring, the valves open and air enters the combustion chamber. Fuel is then injected, and the air-fuel mixture is ignited by a spark plug. The burning fuel produces a rapid increase in pressure within the chamber, and the flapper valves close.

As the pressure in the combustion chamber rises, it exceeds the pressure in the fuel system, and automatically shuts off the flow of fuel. The flaming gases rush down the tailpipe and exhaust to the atmosphere. The momentum given to the working fluid thus provides thrust to propel the engine. Because of the speed with which the combustion gases rush down the tailpipe, they overexpand and produce a partial vacuum within the combustion chamber (middle sketch in figure 4C1.) The ram pressure in the diffuser then exceeds the pressure in the chamber; the flapper valves open, and a fresh supply of air enters the chamber. Because of the decrease in pressure, the pressurized fuel system is able to inject a fresh supply of fuel. As a result of the partial vacuum, a portion of the hot exhaust gas is drawn back into the chamber; the temperature of this gas is high enough to ignite the air-fuel mixture, and a new cycle begins. Note that the spark plug ignition is required only to start the engine; after starting, its combustion cycle is self-sustaining.

The frequency of the combustion cycle is the resonant frequency of the combustion chamber and tailpipe. A formula for resonant frequency of a closed pipe is:

$$\text{Frequency} = \frac{\text{Velocity of sound}}{4 \times \text{length}}$$

The frequency of various pulse-jet engines that have been used in the past ranges from about 50 to over 200 cycles per second.

At the instant of launching, there is no ram pressure in the diffuser of a pulse-jet. For that reason, most pulse-jets are incapable of developing enough static thrust to take off under their own power. They are therefore launched with the help of compressed air injected into the chamber along with the fuel, or from a catapult, or with booster rockets, or by a combination of these means. The speed of a pulse-jet is limited to the low subsonic range by the fact that at higher speeds the ram pressure developed in the diffuser exceeds the chamber pressure at all times throughout the combustion cycle; the flapper valves therefore cannot close, and the cycle can not maintain itself.

4C3. Turbo-jets

A turbo-jet engine is an air-dependent thermal jet-propulsion device. It derives its name from the fact that its compressor is driven by a turbine wheel, which is itself driven by the exhaust gases. Turbo-jets may be divided into two types, depending on the type of compressor. These are CENTRIFUGAL-FLOW TURBO-JETS (fig. 4C2) and AXIAL-FLOW TURBO-JETS (fig. 4C3). Both types are the same in operating principles. The major components of both are an accessory section, compressor section, combustion section, and exhaust section.

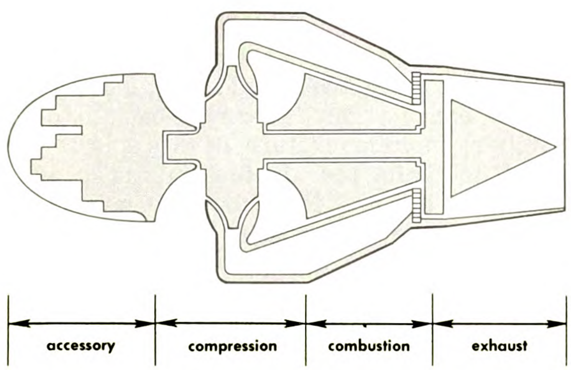


Figure 4C2.–Centrifugal-flow turbo-jet.

The ACCESSORY SECTION serves as a mounting pad for accessories, including the generator, hydraulic pump, starter, and tachometer, for various engine components, such as units of the fuel and oil systems, and for the front engine balancing support.

The primary function of the COMPRESSOR SECTION is to receive and compress large masses of air, and to distribute this air to the combustion chambers. The centrifugal compressor consists of a STATOR, often referred to as a DIFFUSER VANE ASSEMBLE, and a rotor or impeller. The rotor consists of a series of blades which extend radially from the axis of rotation. As the rotor revolves, air is drawn in, whirled around by the blades, and ejected by centrifugal force at high velocity.

The stator consists of diffuser vanes that compress the air and direct it into the various firing chambers. Air leaves the impeller wheel at high velocity. As it passes through the diffuser vanes it enters a larger space; its velocity therefore decreases, and its pressure increases.

The axial compressor is similar to a propeller. The rotor consists of a series of blades set at an angle, extending radially from the central axis. As the rotor of the axial compressor turns, the blades impart energy of motion in both a tangential and axial direction to the ram air entering through the front of the engine. The stator does not rotate. Its blades are set at an angle so as to turn the air thrown off the trailing edge of the first-stage rotor blades, and redirect it into the path of the second-stage rotor blades. One rotor and one stator comprise a single-stage compressor. A number of rotors and stators assembled alternately make up a multistage compressor, as in figure 4C3.

In a multistage compressor, air from the first row of compressor blades is accelerated and forced into a smaller space. The added

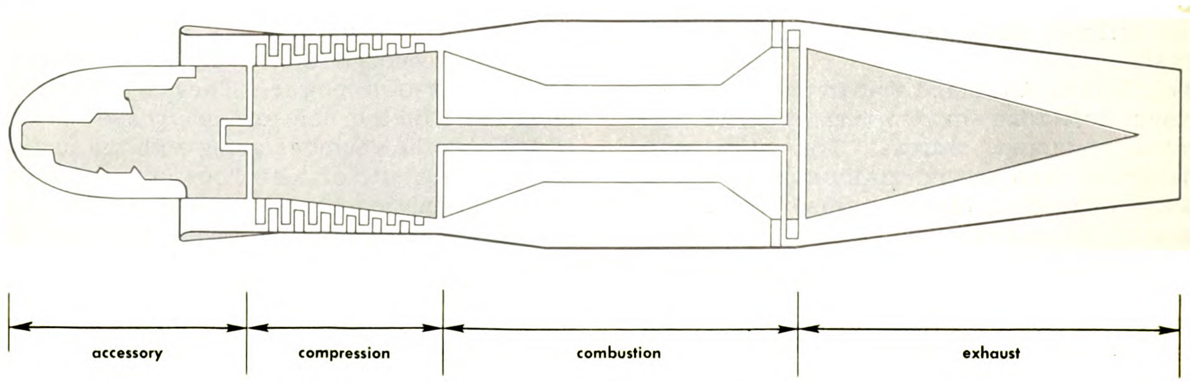


Figure 4C3.–Axial flow turbo-jet.

velocity gives the air greater impact force. This compresses the air into a smaller space, causing its density to increase. The increase in density results in a corresponding increase in static pressure. This cycle of events is repeated in each successive stage of the compressor. Therefore, by increasing the number of stages, the final pressure can be increased to almost any desired value.

The COMBUSTION SECTION includes combustion chambers, spark plugs, a nozzle diaphragm, and a turbine wheel and shaft. The combustion chambers, or BURNERS, in both types of turbo-jet engines, have the same function and produce the same results. But they differ in size and number, depending on the type of engine. In any case, each combustion chamber has the following parts: outer combustion chamber, inner liner, inner liner dome, flame cross over tube, and fuel-injector nozzle.

The outer combustion chamber retains the air so that a high-pressure supply is available to the inner liner at all times. This air also serves as a cooler jacket. The inner liner houses the area in which fuel and air are mixed and burned. Many round holes in the inner liner allow the air to enter and mix with the fuel and high-temperature combustion gases. The forward end of the inner liner is allowed to slide over the dome to accommodate expansion and contraction. The after end of the burners are convergent to increase the velocity of the gases just before they pass through the nozzle diaphragm. The flame cross over tube connects one chamber to the next, allowing ignition to occur in all chambers after the two chambers containing spark plugs have fired.

The EXHAUST SECTION consists primarily of a nozzle and an inner cone. This assembly straightens out the turbulent flow of the exhaust gases caused by rotation of the turbine wheel, and conveys these gases to the nozzle outlet in a more perfect and concentrated gas-flow pattern.

The exhaust-nozzle diaphragm is composed of a large number of curved blades standing perpendicular to the flow of combustion gases and arranged in a circle in front of the turbine wheel. By acting as both a restrictor and a director, this diaphragm increases the gas velocity. Its primary function is to change the direction of the gases so that they strike the turbine-wheel vanes at, or nearly at, a 90° angle. The impact of the high-velocity gases against the buckets of the turbine wheel causes the wheel to rotate. The turbine-wheel shaft is coupled to the compressor-rotor assembly shaft. Thus, part of the energy of the exhaust gases is transformed and transmitted through the shaft to operate the compressor and the engine-driven accessories.

The operation of a turbo-jet may be summarized as follows: The rotor unit of the compressor is brought up to maximum allowable speed by the starter unit, which is geared to the compressor shaft for starting. Air is drawn in from the outside, compressed, and directed to the combustion chambers. Fuel is injected through the fuel manifold under pressure, and mixes with the air in the combustion chambers. Ignition occurs first in the chambers containing the spark plugs, and then in the other chambers an instant later by way of the flame cross over tubes. High-pressure combustion gases and coolant air pass through the exhaust nozzle diaphragm and strike the turbine blades at the most effective angle. Part of the energy of the exhaust stream is absorbed by the turbine, resulting in a high rotational speed. The remainder is thrust. The turbine wheel transmits energy through the coupled turbine and compressor-rotor shafts to operate the compressor. Once started, combustion is continuous.

The afterburner is an important part of jet fighter aircraft; afterburners have limited application in guided missile propulsion. They were developed to give additional thrust when needed for short periods of time, as in launching or during a steep programmed climb.

The additional thrust is obtained by burning additional fuel in the tailpipe section. That portion of the air which served only as a coolant for the main combustion chambers is sufficient to support combustion of the additional fuel. The added thrust is large, but the over-all efficiency of the turbo-jet decreases because the specific fuel consumption is greatly increased. During a missile launching, an afterburner could provide approximately 30% increase in thrust; when the missile reaches a speed of 600 mph, an afterburner can increase its thrust by from 70% to 120%.

4C4. Ram-jet

A ram-jet engine derives its name from the ram action that makes its operation possible. (This engine is sometimes referred to as the athodyd, meaning aerothermodynamic duct).

Ram-jet operation is limited to altitudes below about 90,000 feet because atmospheric oxygen is necessary for combustion. The velocity that can be attained by a ram-jet engine is theoretically unlimited. The faster a ram-jet travels the more efficiently it operates, and the more thrust it develops. But its upper speed is limited, in practice, to about Mach 5.0, because of frictional heating of the missile skin. The major disadvantage of a ram-jet is that the higher the speed at which it is designed to operate, the higher the speed to which it must be boosted before automatic operation can begin.

Basically, a ram-jet consists of a cylindrical tube open at both ends, with a fuel-injection system inside. The engine is extremely simple in design, and it has no moving parts. Even though all ram-jets contain the same basic parts, the structure of these parts must be modified to produce satisfactory operation in the various speed ranges. The principal parts of a ram-jet engine are a diffuser section, and a combustion chamber that contains fuel injectors, spark plugs, flame holder, and an exhaust nozzle.

The DIFFUSER SECTION serves the same purpose in the ram-jet as it does in the pulse-jet. It decreases the velocity and increases the pressure of the incoming air. Since there is no wall or closed grill in the front section of a ram-jet, the pressure increase of the ram air must be great enough to prevent the escape of the combustion gases out the front of the engine. Diffusers must be especially designed for a specific entrance velocity, or predetermined missile speed. In other words, the desired pressure barrier is developed only when air is entering the diffuser at the speed for which that particular diffuser was designed.

The COMBUSTION CHAMBER is of course the area in which burning occurs and high-pressure gases are generated. The fuel injectors are connected to a continuous-flow fuel supply system, adequately pressurized to permit fuel to flow against the high pressures that exist in the forward section of the combustion chamber. Combustion is started by a spark plug; once started, it is continuous and self-supporting. The flame holder prevents the flame front from being swept too far toward the rear of the engine, thus stabilizing and restricting the actual burning to a limited area. The flame holder also insures that the combustion-chamber temperature will remain high enough to support combustion.

The EXHAUST NOZZLE performs the same function as in any jet-propulsion engine.

A SUBSONIC RAM-JET engine cannot develop static thrust; therefore, it cannot take off under its own power. If fired at rest, high-pressure combustion gases would escape out the front as well as the rear. For satisfactory operation, the engine must be boosted to a suitable subsonic speed so that the ram air entering the diffuser section develops a pressure barrier high enough to confine the escape of combustion gases to the rear only. Figure 4C4 is a diagram of a subsonic ram-jet engine. Note the simple tubular construction, and the openings at front and rear.

As ram air passes through the diffuser section (fig. 4C4), the velocity of the air decreases while the pressure increases. This is brought about by the increase in cross section of the diffuser, in accordance with Bernoulli's theorem for incompressible flow. Fuel is sprayed into the combustion chamber through the fuel injectors. The atomized fuel mixes with the incoming air, and the mixture is ignited by the spark plug. As previously stated, burning is continuous after initial ignition, and no further spark plug action is needed.

The gases that result from the combustion process expand in all directions, as shown by the arrows in the central part of the combustion chamber (fig. 4C4). The gases, as they expand in the forward direction, are stopped by the barrier of high-pressure air and the internal sloping sides of the diffuser section, as indicated in the diagram by the short, wide black arrows. The only avenue of escape remaining for the combustion gases is through the exhaust nozzle, and here another important energy conversion occurs: The pressure energy of the combustion gases is converted to velocity. The gases enter the exhaust nozzle at less than the local speed of sound. But, while they pass through the convergent nozzle, the pressure energy of the gases decreases

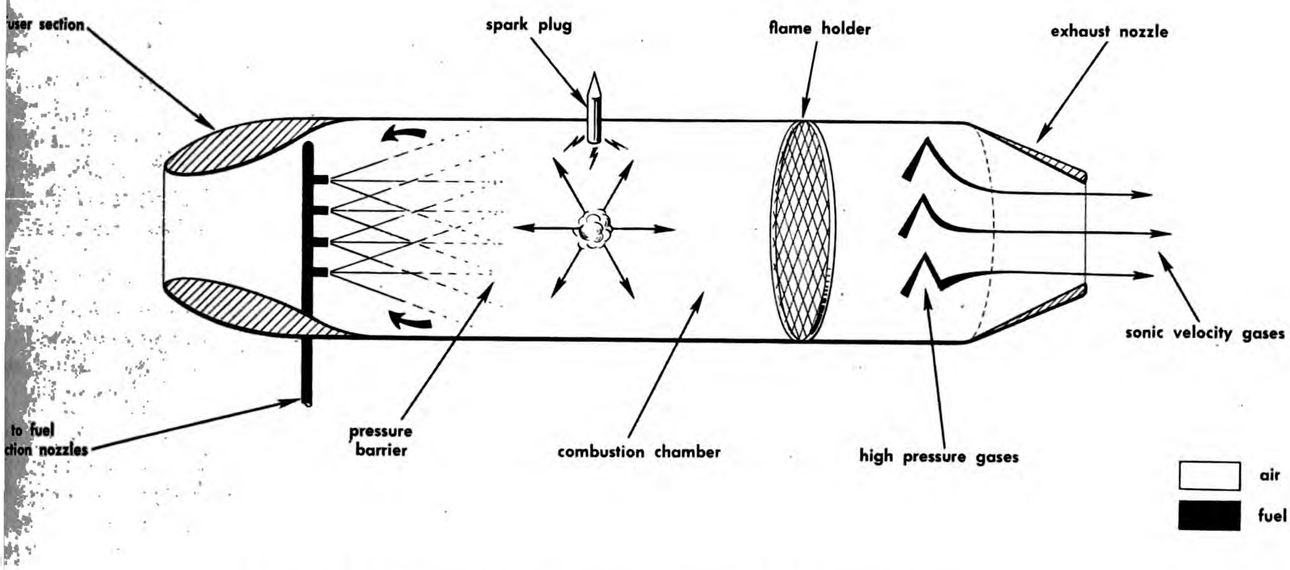


Figure 4C4.—Structure and combustion processes of a subsonic ram-jet.

and the velocity increases up to the local speed of sound at the exhaust nozzle exit.

Thrust is developed in the ram-jet as a result of the unbalance of forces acting in the forward and rearward directions. The bombardment of combustion gases against the sloping sides of the diffuser and the ram-air barrier exert a force in the forward direction. This forward force is not balanced by the combustion gases that escape through the exhaust nozzle. The unbalanced force constitutes the thrust that propels the missile.

In order to operate, a **LOW-SUPERSONIC RAM-JET** must be boosted to a supersonic speed, approximately equal to its operating speed, before ignition. When the forward speed of the ram-jet becomes supersonic, a normal shock wave forms at the entrance to the diffuser section. The location of this shock wave is shown in figure 4C5. On the upstream side of the normal shock wave, the free-stream air is moving at a low supersonic velocity. As the supersonic air passes through the shock wave, its velocity drops abruptly to a subsonic value, with a corresponding increase

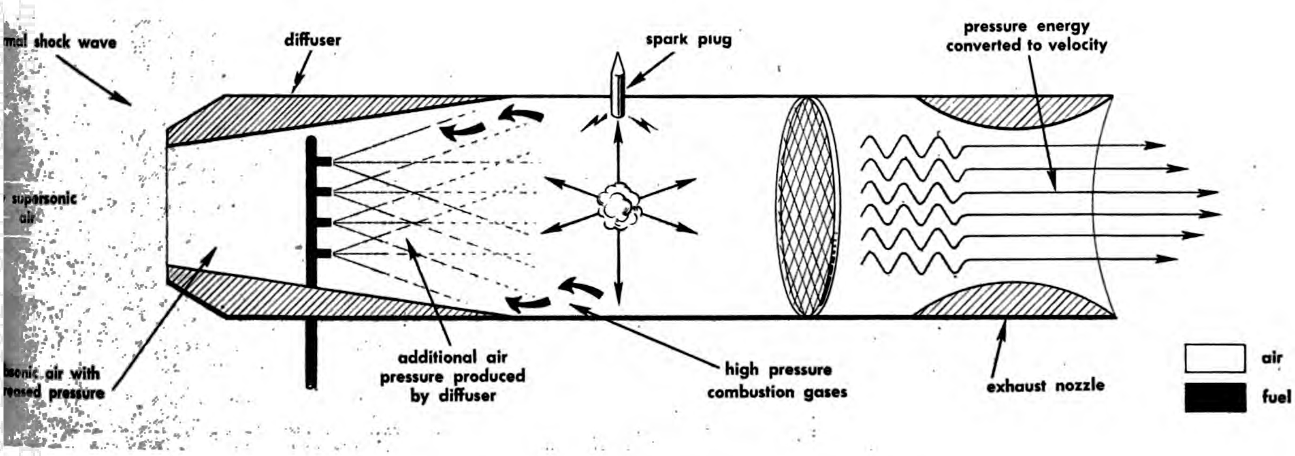


Figure 4C5.—Structure and combustion processes of a low supersonic ram-jet.

in pressure. Thus the shock wave produces a sudden increase in air pressure at the diffuser entrance. As the compressed subsonic air flows through the diverging diffuser section, an additional increase in pressure and decrease in velocity occurs.

The combustion process is essentially the same as that in a subsonic ram-jet. Fuel is mixed with the highly compressed air, the mixture is ignited initially by a spark plug, and burning is continuous thereafter. The potential energy possessed by the combustion gases is converted into kinetic energy by the exhaust nozzle.

The convergent-divergent nozzle shown in figure 4C5 allows the gases to exceed the local speed of sound. Therefore, with proper design modifications, the ram-jet engine can travel efficiently at supersonic speed.

Now, assume that we want to design a ram-jet that will travel at HIGHER SUPERSONIC SPEEDS, say Mach 2.0. At speeds of around Mach 2.0, shock waves formed at the diffuser inlet are oblique, rather than normal. Air velocity in front of an oblique shock wave is high supersonic. When supersonic free-stream air passes through an oblique shock wave, an increase in pressure and a decrease in velocity occur, but the velocity is still supersonic. For example, air with a free-stream velocity of 1,500 mph may pass through an oblique shock wave and still have a velocity of 900 mph. Also, when supersonic air flows through divergent-type diffuser actions, as shown in figures 4C4 and 4C5, the velocity of that air increases and the pressure decreases. Therefore, the diffuser design for high-supersonic ram-jets must be modified so that in progressing from diffuser inlet to combustion-chamber entrance, the obliqueness of the shock wave successively decreases until a normal shock wave followed by subsonic flow is produced.

This energy transformation is achieved by using a diffuser of the type shown in figure 4C6. The diffuser center body decreases the obliqueness of the shock waves, allowing supersonic air to flow inside the diffuser inlet.

As supersonic flow passes through the divergent section of the diffuser, the velocity is steadily decreased and the pressure correspondingly increased. But, at some predetermined point in the diffuser, air velocity approaches the sonic value and a normal shock wave forms. As previously stated, when low-supersonic air flows through a normal shock wave, an abrupt decrease in velocity and increase in pressure results. The subsonic air produced by the normal shock wave flows through the divergent section of the diffuser, where it undergoes an additional velocity decrease and pressure increase. Here again the diffuser has achieved a pressure barrier at the entrance to the combustion chamber. The combustion process is the same as that described for the subsonic ram-jet. The exhaust nozzle shown in the diagram is of the

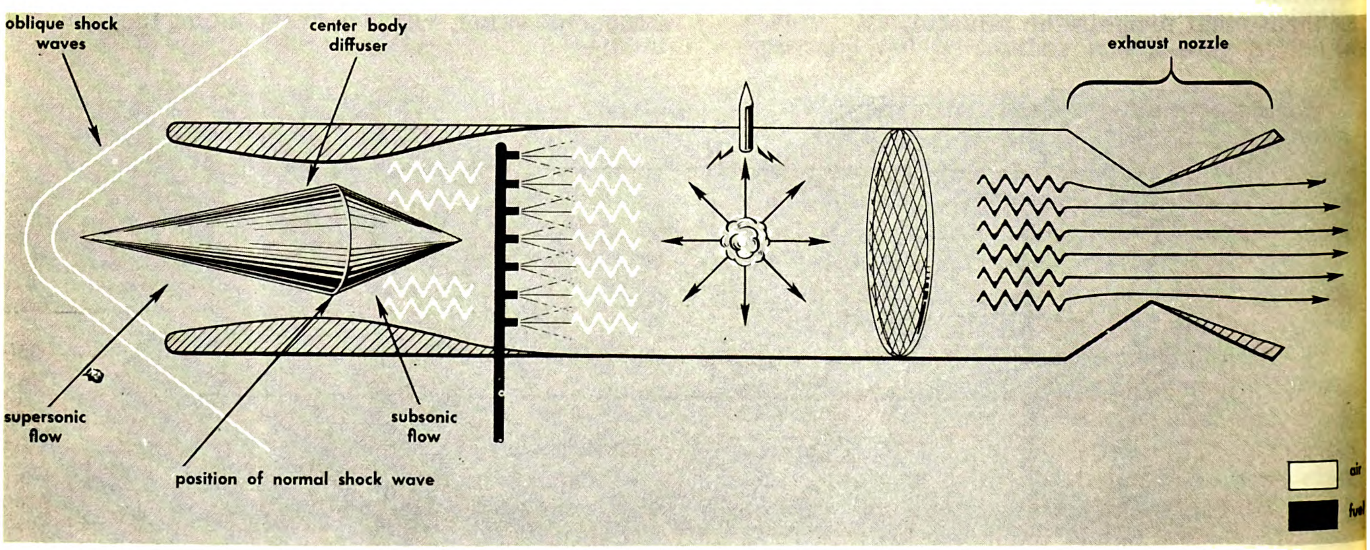


Figure 4C6.—Structure and combustion processes of a high supersonic ram-jet.

convergent-divergent type designed to produce supersonic flow at the exit.

A ram-jet is designed to operate best at some given speed and altitude. The pressure recovery process in a diffuser designed for oblique shock waves is more efficient than that in diffusers designed for subsonic flow or single normal shock waves. For that reason the ram-jet engine operates best at high supersonic speeds.

D. Rocket Motors

4D1. General

Unlike a jet engine, a rocket carries within itself all the mass and energy required for its operation. It is independent of the surrounding medium. In a rocket, the chemical reaction takes place at a very rapid rate. This results in higher temperatures, higher operating pressures, and higher thrust development than in jet engines. Because of the high pressures developed in rocket motors, the convergent-divergent nozzle is used so that more of the energy can be extracted from the gases after they have passed the throat section. The basic principles involved in the action of other jet-propulsion units also apply to rockets.

Depending on the physical state of the propellant used, rockets are designated as either SOLID or LIQUID type.

A solid rocket has a short burning time, simple design, heavy construction, and non-intermittent operation. It is therefore primarily used for booster units, and as a powerplant for relatively short-duration, high-speed missiles. But recent research seems to indicate that solid fuels will have increasing future applications in long-range missiles. The Navy's Polaris (IRBM) is propelled by a solid-fuel rocket.

The liquid rocket unit has a longer burning time, relatively complicated design, and intermittent operation possibilities. This system has been widely used as a powerplant for high-altitude, long-range missiles.

4D2. Liquid-fuel rockets

The major components of a liquid-rocket system are the propellant, propellant-feed system, combustion chamber, igniter, and exhaust nozzle. The propellant-feed system is the only one which has not been explained, in principle, in the preceeding sections of this chapter. Feed systems may be of the pressure-feed type or the pump-feed type.

Pressure-feed systems may be subdivided into stored-pressure and generated-pressure systems. In the stored-pressure system, air or some other gas is stored under pressure in the missile before launching. It is injected, in controlled amounts, into the propellant storage tanks, causing a pressurized flow toward the combustion chamber. In a generated-pressure system, substances are carried within the missile to generate the high-pressure gas as it is needed. An example of such a substance is hydrogen peroxide, which, when passed through a catalyst, decomposes to form a high-pressure vapor. This vapor is then injected into the propellant storage tanks.

Many other devices such as valves, regulators, delivery tubes, and injectors, are necessary for the successful operation of either system.

Figure 4D1 shows the general relationship of the various major parts of a typical stored-pressure feed system. In the system shown, air is stored under a pressure of 200 psi. The hand-arming valve is opened manually, just before launching. This allows the system to be pressurized up to the motor-start valve. The air-pressure regulator decreases the pressure to the desired value required for operation of the system components—in this case 100 psi.

The motor-start valve is electrically operated. It is opened from a safe distance after all personnel have cleared the immediate launching area. Air at 100 psi enters and pressurizes the fuel and oxidizer tanks. These tanks must be made of material that is not affected by the respective propellants. In addition, they must be strong enough to withstand the added air pressure. At the same time the propellant tanks are pressurized, air also enters the hydraulic accumulator and pressurizes the hydraulic fluid. The hydraulic fluid displaces the piston in the propellant valve actuating cylinder, which in turn opens the propellant valves. Fuel and oxidizer,

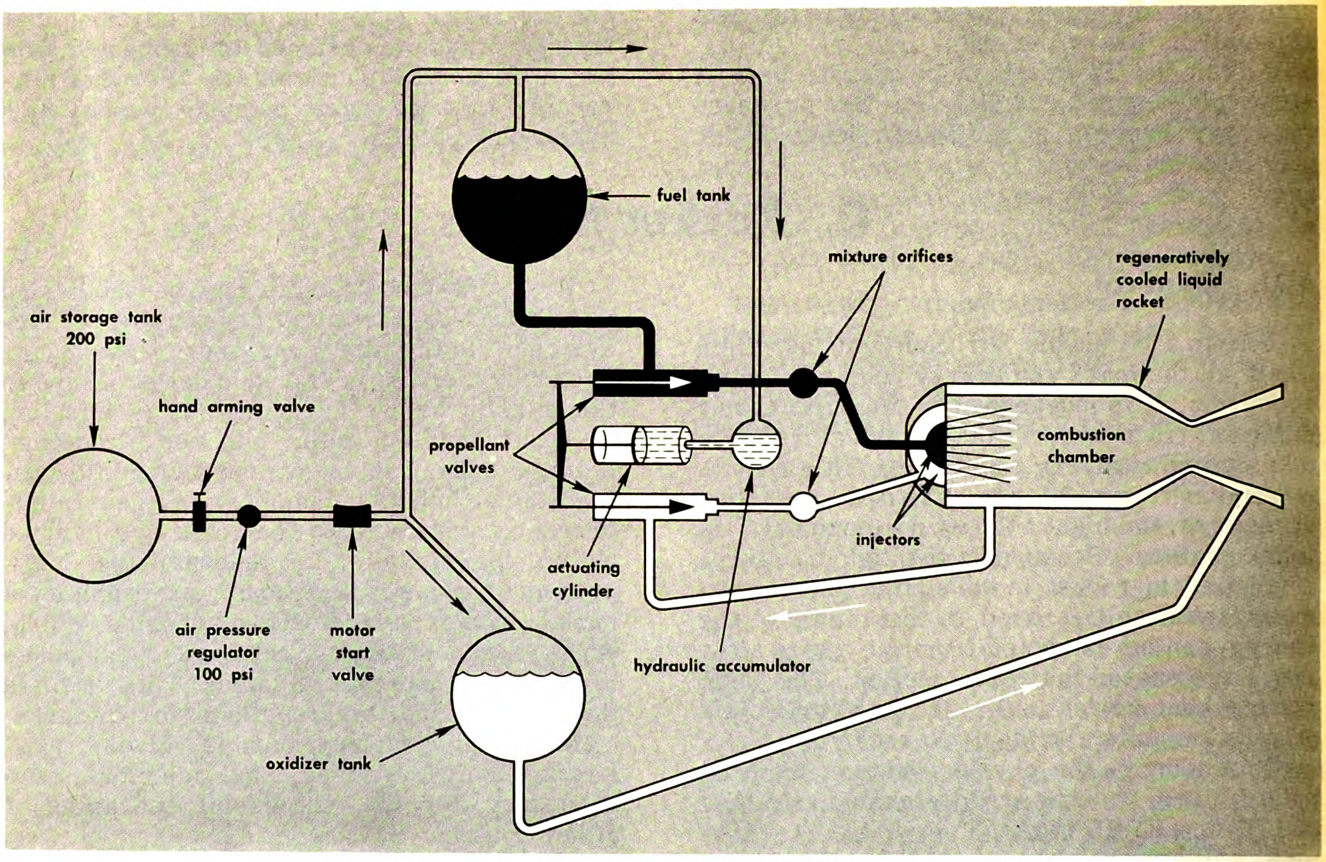


Figure 4D1.—Stored-pressure feed system of a liquid rocket.

under pressure, now flow through the respective mixtures orifices, which regulate the flow so that the correct mixture ratio is maintained. These orifices are simply restrictions in the line, and are flow-checked prior to installation. In some cases the injectors perform this operation, and orifices are not necessary. The propellants are atomized by the injectors. Note that the oxidizer first circulates between the walls of the combustion chamber before passing through the cut-off valve. This action is called REGENERATIVE COOLING.

Pump-feed systems are used with powerplants designed to burn large volumes of propellants, and with plants requiring a high weight rate of flow. A pump-feed system consists of a fuel pump and an oxidizer pump, both driven by a turbine wheel. Power for driving the turbine wheel may be provided by a gas generated by chemicals carried within the missile for that purpose (turbine-pump system), or the turbine wheel may receive its power from the exhaust gases of a rocket motor (turbo-pump system).

Because of the intense heat developed in liquid-rocket combustion chambers, it is important that the inner walls of the chamber, throat, and exit be cooled. Uncooled operation over a prolonged period reduces physical strength and may even melt parts of the motor.

The regenerative cooling method shown in figure 4D1 is often used. Before injection into the chamber, the fuel or oxidizer is circulated from front to rear between the walls of the combustion chamber. The heat absorbed by the fuel or oxidizer cools the chamber and adds to the energy originally contained in the propellant.

A film-cooling procedure consists of low-velocity injection of a portion of the fuel, oxidizer, or some nonreactive liquid into the chamber at critical points. The fluid forms a protective film on the inner walls, and absorbs heat from the walls as it evaporates.

Liquid propellants may be classified either as monopropellants or bipropellants. Monopropellants are those in which the fuel and oxidizer are combined as a single substance. This may be a physical combination—for example hydrogen peroxide mixed with ethyl alcohol, or a chemical combination such as nitromethane. Monopropellants are stable at ordinary temperatures, but when activated by an ignition system they decompose and liberate hot combustion gases. Monopropellants are seldom used in guided missiles because of the possibility of detonation being propagated from the combustion chamber, through the fuel lines, to the storage tanks.

The fuel and oxidizer of a bipropellant are kept apart until they are injected into the combustion chamber. Most liquid propellants for guided missiles are of this type.

Aniline, hydrazine hydrate, and ethyl alcohol are among the more commonly used liquid rocket fuels. Analine is an oily clear liquid with a specific gravity of 1.022. It has a boiling point of about 363° F and a freezing point of about 21° F. On contact with red fuming nitric acid, it ignites spontaneously. A fuel and oxidizer combination that reacts in this manner is said to be HYPERGOLIC. This combination was successfully used in the WAC Corporal missile.

Hydrazine hydrate is a colorless liquid, slightly heavier than water. It is explosive when its concentration is above 25%. Hydrazine hydrate gives a hypergolic reaction with hydrogen peroxide.

Ethyl alcohol is a clear liquid, lighter than water. It is stable to shock and temperature changes. It is readily available because of its wide commercial market in the chemical and liquor industries.

Liquid oxygen, and various forms of nitric acid, are among the most commonly used oxidizers in liquid rockets. Liquid oxygen is made by liquefying air and boiling off the nitrogen and other gases. This bluish liquid has a boiling point of about minus 297° F, and a freezing point of minus 363° F. Because of its low boiling point, its rate of evaporation is very high. For this reason, storage and shipment to launching areas presents serious problems, and results in appreciable loss. When poured on metal at ordinary temperature, liquid oxygen acts like water dropped on a red-hot stove. Evaporation loss in the German V-2 missile was about 4.4 pounds per minute between the time of fueling and launching.

The extremely low temperature of liquid oxygen causes water vapor from the surrounding atmosphere to collect and freeze on pipes and valves. This is a serious problem, which has yet to be fully solved. Liquid oxygen is noncorrosive and nontoxic, but will cause severe damage if it comes into contact with skin.

Nitric acid is used in several different forms as an oxidizer for liquid rockets. The most commonly used and the most powerful of these is RED FUMING NITRIC ACID (RFNA), which consists of nitric acid in which nitrogen dioxide is dissolved. It varies in color from orange to brick red, and gets its name from the reddish color of the nitric oxide fumes it gives off. RFNA is highly corrosive, and stainless steel must be used for storage tanks and delivery pipes. Its high vapor pressure presents storage and transfer problems. The fumes are extremely poisonous, and severe burns result from bodily contact with the liquid. This oxidizer has been successfully used with analine, giving up approximately 63.5% of its oxygen content for combustion.

Hydrogen peroxide is a colorless liquid which, in concentrations of from 70% to 90%, may be used as a monopropellant in guided missiles. When in contact with a suitable catalyst it decomposes, forming steam and gaseous oxygen. When 90% hydrogen peroxide decomposes, about 42% of the total weight of the decomposition products is gaseous oxygen. Therefore, it is also used as an oxidizer with such fuels as alcohol and hydrazine hydrate. A third use for hydrogen peroxide is as a pressurizing agent. The gaseous products of decomposition may be jetted against a turbine wheel which drives fuel and oxidizer pumps connected to the turbine shaft.

4D3. Solid-fuel rockets

A solid rocket unit consists of the propellant, combustion chamber, igniter, and exhaust nozzle. A typical solid rocket motor is shown in figure 4D2.

The combustion chamber of a solid rocket serves two purposes. First, it acts as a storage place for the propellant. Second, it serves as a chamber in which burning takes place. Depending on the grain configuration used,

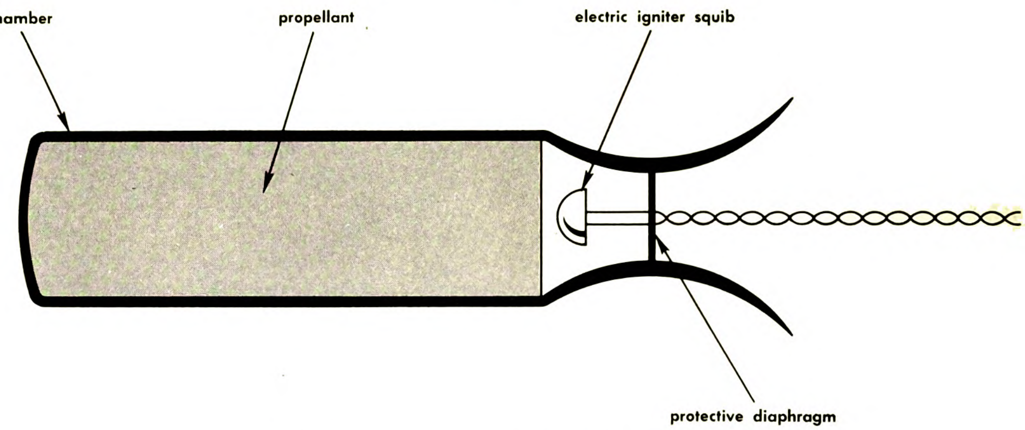


Figure 4D2.–Components of solid rocket motor.

this chamber may also contain a device for holding the grain in the desired position, a trap to prevent flying particles of propellant from clogging the throat section, and resonance rods to absorb vibrations set up in the chamber.

The igniter consists of a small charge of black powder, or some other material that can be easily ignited by either a spark discharge or a hot wire. As it burns, the igniter produces a temperature high enough to ignite the main propellant charge.

The exhaust nozzle serves the same purpose as in any other jet-propulsion system. It must be of heavy construction, because of the high temperatures of the exhaust jet.

Operation of a solid rocket is simple. The propellant charge is ignited electrically from a safe distance. The igniter squib assembly is blown out, and the rocket burns continuously until the propellant supply is exhausted.

Cooling is not usually a serious problem in a solid rocket, because the burning time is relatively short. One method of preventing excessive heat from reaching the chamber walls is to use a hollow-restricted charge. With a charge of this type, burning takes place only on the inner surface, and the outer walls of the grain tend to act as an insulator. This becomes less and less effective as the grain is burned thinner and thinner.

Solid propellant charges are classified as restricted burning or unrestricted burning. A RESTRICTED-BURNING charge has some of its exposed surfaces covered with an INHIBITOR. This makes it possible to control the burning rate by confining the burning area to the desired surface or surfaces. The use of inhibitors lengthen the burning time of the charge, and helps to control the combustion-chamber pressure. A burning cigarette can be considered as a model of an inhibited rocket grain, with the paper representing the inhibitor.

UNRESTRICTED-BURNING charges are permitted to burn on all surfaces at once. The unrestricted grain delivers a relatively large thrust for a short time, and the restricted grain yields a smaller thrust for a longer time.

The burning characteristics of a solid propellant depend on its chemical composition, initial temperature, combustion-chamber temperature and pressure, gas velocity adjacent to the burning surface, and size and shape of the grain. One propellant grain may burn in such a way that the burning area remains constant, producing constant thrust. This type of burning is known as NEUTRAL BURNING. Another grain may increase its burning area as burning progresses. In this case, PROGRESSIVE BURNING is taking place. Still another grain may show a constantly decreasing burning area as burning progresses. This is called DIGRESSIVE BURNING.

The BURNING RATE of a solid propellant is the rate at which the grain is consumed; it is a measure of linear distance burned, in inches per second, in a direction perpendicular to a burning surface.

As stated earlier, thrust depends on mass rate of flow and the change in velocity of the working fluid. For large thrust, a large burning area is necessary in order to yield a

arge mass flow. A smaller burning area ›roduces less mass flow and less thrust. Therefore, by varying the geometrical shape md arrangement of the charge, the thrust leveloped by a given amount of propellant in a ;iven combustion chamber can be greatly nfluenced.

A restricted-burning charge is usually a solid cylinder which completely fills the com- bustion chamber and burns only on the end. The thrust is proportional to the cross-section area of the charge, and burning time is pro- portional to length. An unrestricted burning charge is usually hollow, and burns on both he outside and inside surfaces. Thrust is again proportional to the burning area. Since the inside area increases while the outside area decreases during burning, it is possible to maintain a nearly constant burning area. The burning time of hollow grains depends on the WEB THICKNESS—the distance between the inside and outside surfaces.

One limitation of solid propellants is sen- sitivity to temperature. The initial tempera- ture of a grain noticeably affects its perform- ance. A given grain will produce more thrust on a hot day than it will on a cold day. A grain designed to produce 1,000 pounds of thrust at 80° F may deliver only 600 pounds of thrust at 30° F. The initial temperature also affects the burning rate. Because of these characteristics, solid propellants must be stored in areas of controlled temperature until they are used. The percentage change in thrust per degree Fahrenheit temperature change is referred to as the TEMPERATURE SENSITIVITY of the propellant.

Temperature also affects the physical state of solid-propellant grains. At extremely low temperatures, some grains become brittle and are subject to cracking. Cracks increase the burning area and burning rate and therefore increase the combustion-chamber pressure. If this pressure exceeds that for which the chamber was designed, the chamber may ex- plode. A propellant exposed to high tempera- ture before firing may lose its shape, and become soft and weak. This, too, results in unsatisfactory performance. The temperature range for most solid propellants is from about 25° F to 120° F.

PRESSURE LIMITS play an important part in solid propellant performance. Below a cer- tain chamber pressure, combustion becomes highly unstable. Some propellants will not sustain combustion at atmospheric pressure. Ordinarily, chamber pressure for solid pro- pellants must be relatively high. For a given propellant composition and burning area, the chamber pressure is determined by the area of the exhaust nozzle throat. If the throat area is too large, for example, proper chamber pressure cannot be maintained.

Decomposition and hygroscopic tendencies are other weaknesses of solid propellants, but both can be minimized by the use of certain additives.

Some of the more common propellants are discussed below. The chemical formulas of some of them are given, to show the carbon and/or hydrogen content, and the oxygen con- tent of the oxidizers.

One of the first solid propellants used was BLACK POWDER. Its approximate composi- tion is:

Potassium nitrate (KNO_3)	61.6%
Charcoal (C)	23.0%
Sulphur (S)	15.4%

Both charcoal and sulphur react readily with oxygen. Potassium nitrate, as shown by its formula, contains large quantities of oxygen. The three ingredients are thoroughly mixed, using some substance such as glue or oil as a BINDER.

When heat is applied to black powder, the potassium nitrate gives up oxygen. The oxygen reacts with the sulphur and carbon, producing intense heat and large volumes of carbon dioxide and sulphur dioxide. These two gases make up the major part of the exhaust jet. The heat produced by the reaction gives high velocity to the exhaust gases. Black powder has a specific impulse of about 65 lb-sec/lb. One of its drawbacks is that it is quite sensi- tive to storage temperatures, and tends to crack. Its exhaust velocity ranges from 1,500 to 2,500 feet per second. It is now used pri- marily for signal rockets, and as an igniter for other solid-propellant grains.

BALLISTITE is a double-base propellant; it contains two propellant bases, NITROCEL- LULOSE and NITROGLYCERINE. It also con- tains small amounts of additives, each per- forming a specific function. A STABILIZER absorbs the gaseous products of slow decom- position, and reduces the tendency to absorb moisture during storage. A PLASTICIZER serves as a binding agent. An OPACIFIER is

added to absorb the heat of reaction and prevent rapid thermal decomposition of the unburned part of the grain. A FLASH DEPRESSOR cools the exhaust gases before they escape to the atmosphere, thus preventing a burning-tail effect. A typical ballistite composition is

Nitrocellulose $C_{24}H_{40}O_{20}(NO_3)$	51.38%	(propellant)
Nitroglycerine $C_3H_5(NO_3)_3$	43.38%	(propellant)
Diethylphthalate	3.09%	(Plasticizer)
Potassium nitrate	1.45%	(flash depresser)
Diphenylamine	0.07%	(stabilizer)
Nigrosine dye	0.10%	(opacifier)

Ballistite has a specific impulse of about 210 lb-sec/lb. Its exhaust is relatively smokeless. Storage temperatures between 40° F and 120° F are necessary to prevent rapid decomposition. The ingredients of ballistite are subject to detonation, and are toxic when they come in contact with the skin. The manufacturing process is difficult and dangerous.

GALCIT consists of about 25% asphalt-oil mixture, which serves as both fuel and binder, and 75% potassium perchlorate ($KClO_4$), which serves as an oxidizer. In its finished form, Galcit resembles stiff paving tar. Recommended temperature limits for firing are 40° F to 100° F. The specific impulse of galcit is about 186 lb-sec/lb. It is quite stable to temperature; storage temperature limits are minus 9° F to 120° F. Galcit is relatively easy to manufacture. It is nonhygroscopic—that is, it does not absorb moisture. Its major disadvantage is that its exhaust develops dense clouds of white smoke.

NDRC PROPELLANTS were developed through research sponsored by the National Defense Research Committee. A typical composition consists of about equal parts of ammonium picrate and sodium nitrate (46.5% each), and 7% resin binder (usually urea formaldehyde). This propellant has good thermal stability. It is hygroscopic, and must therefore be stored in sealed containers. Heavy smoke develops in the exhaust gases.

4D4. Nuclear-powered rockets

Serious consideration is being given to the use of nuclear power for missile propulsion. A nuclear powerplant would greatly increase both the speed and range of missiles. Present propulsion systems would become obsolete as major powerplants. But they may still serve as boosters for takeoff and initial acceleration, to prevent radioactive contamination of the launching area.

One of the main advantages in the use of nuclear power is that it provides an almost inexhaustible source of heat. In a missile propelled by nuclear energy, the fuel supply would remain practically constant throughout the flight. Enough fuel to start the reaction would be enough for sustained operation. But other material, such as water, will be required in the missile to absorb the heat developed by the powerplant, and be accelerated to produce thrust.

The major problems confronting the engineers are protecting the launching personnel from radiation damage, and developing a nuclear powerplant small enough to be carried in a guided missile. Many years of extensive technical development may be needed before nuclear energy can be harnessed for use as a missile powerplant. But the outlook is promising.

CHAPTER 5

MISSILE CONTROL SYSTEMS

A. Introduction

5A1. General

This chapter will introduce some of the numerous devices that may be used to control the flight of a guided missile. We will discuss four types of control systems: pneumatic, pneumatic-electric, hydraulic-electric, and electric. Throughout the chapter we will deal with general principles, rather than the actual design of any specific missile.

5A2. Definitions

A missile GUIDANCE system keeps the missile on the proper flight path from launcher to target, in accordance with signals received from control points, from the target, or from other sources of information. The missile CONTROL system keeps the missile in the proper flight attitude. For example, the missile axis must lie along the desired trajectory, rather than at an angle. The missile must be roll stabilized; that is, a fixed plane through the missile axis must remain parallel to a fixed reference plane outside the missile. Flight attitude stabilization is absolutely necessary if the missile is to respond properly to guidance signals. For example, assume that the missile has rolled 90 degrees clockwise from the proper attitude. Now, if it receives a "right turn" command from the guidance system, operation of the control surfaces will actually turn the missile downward, rather than to the right. But if the control system keeps the missile in the proper attitude, guidance signals will be correctly interpreted, and will produce the desired correction in the missile flight path.

When the control system determines that a change in missile attitude is necessary, it makes use of certain controllers and actuators to move the missile control surfaces. The guidance system, when it determines that a change in missile course is necessary, uses these same devices to move the control surface. Thus the guidance and control systems overlap. For convenience, we will assume that the controllers and actuators are a part of the control system, rather than the guidance system. We can therefore say that the output signals from the guidance system are put into effect by a part of the control system.

To summarize: the missile control system, discussed in this chapter, is responsible for missile attitude control. The guidance system, discussed in chapter 6, is responsible for missile flight path control.

5A3. Purpose and function: basic requirements

The control system is made up of several sections that are designed to perform, insofar as possible, the functions of a human pilot. To accomplish this purpose, the control surfaces must function at the proper time and in the correct sequence. For example, in driving your car, you remember that you must make a turn at a certain distance from the starting point. You therefore anticipate the turn. In a missile control system, the remembering is done by INTEGRATING DEVICES and the anticipation is done by RATE DEVICES. These devices will be described later.

The first requirement of a control system is a means of a sensing when control operations are needed. The system must then determine what controls must be operated, and in what way. For example, the system may sense that the missile nose is pointing to left of the desired course. Obviously, right rudder is required. (Other missiles may make use of different control surfaces.) The length of time rudder control is needed depends on the size of the error. Should the attitude deviation be to one side and also either up or down, simultaneous action by rudder and elevator controls would be needed.

5A4. Factors controlled

Missile course stability is made possible by devices which control the movement of the missile about its three axes. The three flight control axes are shown in figure 5A1. These are the pitch, yaw and roll axes.

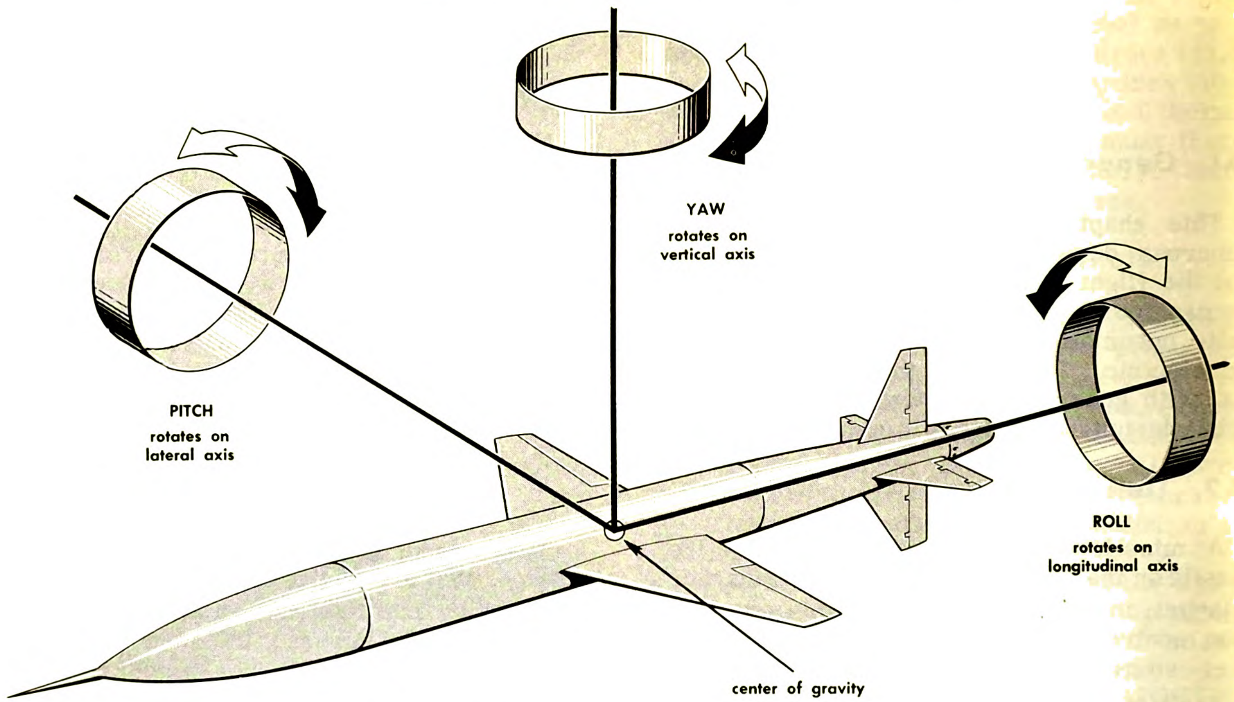


Figure 5A1.—Three control axes of a missile.

PITCH. In certain missiles, pitch control is obtained by the use of elevators similar to those used on light airplanes. Other methods will be described in the next section of this chapter. For the present, it is sufficient to say that pitch control means control of the up-and-down movements of the missile, as shown in the illustration.

YAW. Missile movement about the yaw axis is controlled by the rudder. Other methods for controlling yaw will be covered in the following section of this chapter.

ROLL. Roll deviations are controlled by differential movements of rudders, elevons, or other flight control surfaces.

5A5. Methods of control

CONTROL SURFACES. The primary control surfaces of aircraft, and of some missiles, are rudder, aileron, and elevator. The functions of these surfaces are shown in figure 5A2. The top view shows how the rudder controls the direction of travel. The rudder is attached to a section of the tail structure called the vertical stabilizer. In addition to course control, the rudder is also used in yaw stabilization of the plane or missile.

The center view of figure 5A2 shows how the ailerons can control roll. The ailerons are attached to the trailing edges of the main lifting surfaces. When one aileron is lowered, the opposite aileron is raised. Usually, the ailerons are coupled to other surfaces in such a manner that good roll control is obtained.

The elevators are attached to a section of the tail assembly called the horizontal stabilizer. The elevators give pitch control; both elevators go up and down simultaneously.

A study of the drawings will show that control action is obtained by the control surfaces when they present opposition to air flow in such a manner that a force is produced. This force, pushing against the control surface, causes the wing or tail to which the surface is attached to move in a direction opposite to the control surface movement.

But this type of control is not suitable for use at high altitudes, because the air is so thin that it produces very little force against the control surfaces. High speeds introduce other problems so that the basic control surfaces

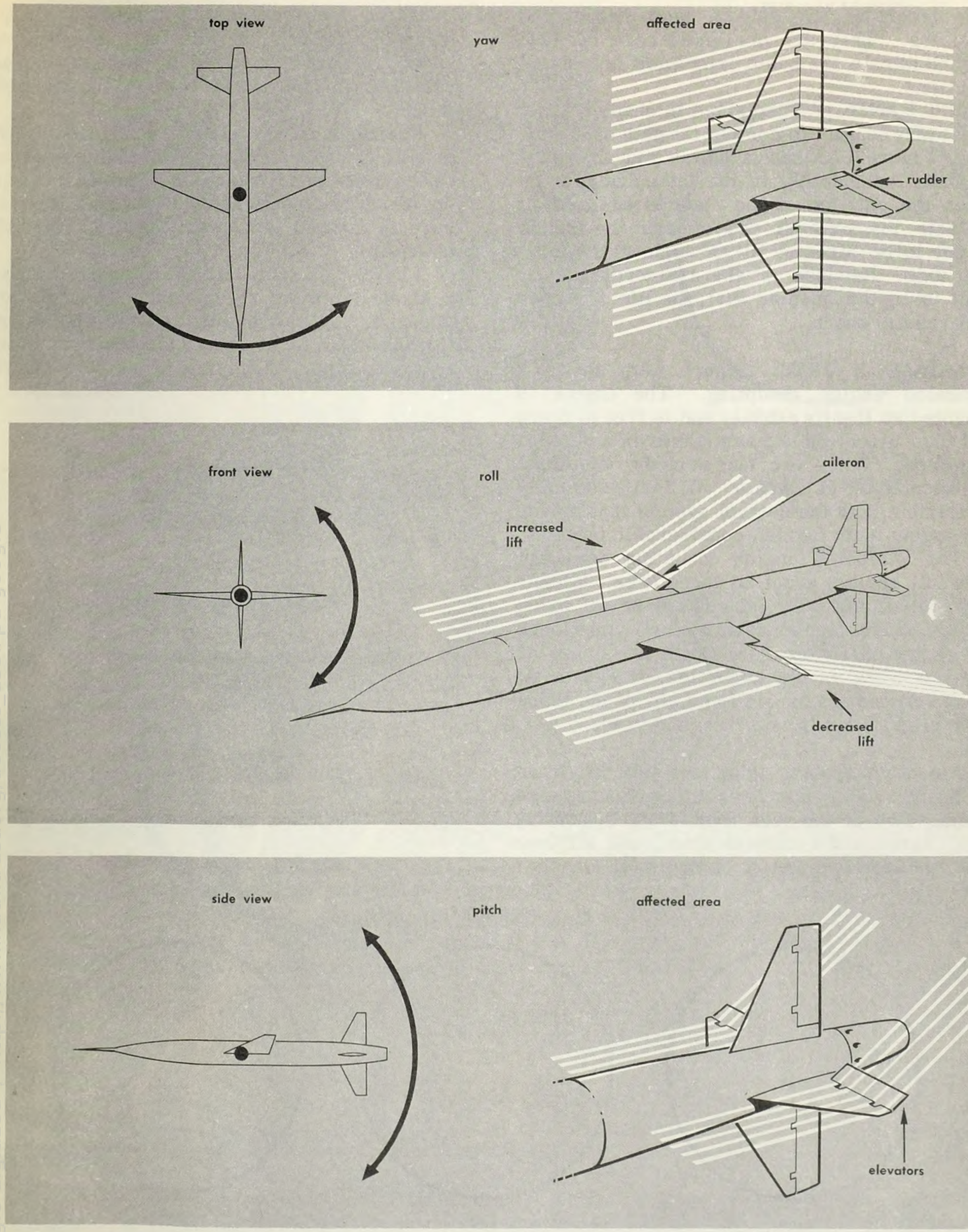


Figure 5A2.—Functions of primary control surfaces.

just described are seldom used with guided missiles. They are presented here because they illustrate the basic principles of control functions.

JET VANES. As explained in chapter 2, jet vanes may be used to control the path of a missile. Figure 5A3 shows how a movable vane is installed directly in the jet exhaust path. When the position of the vane is changed, it deflects the exhaust and causes the engine thrust to be directed at an angle to the missile axis. Because of the tremendous heat built up by the burning fuel, the life of a control vane is short.

MOVABLE JETS. Figure 5A4 shows a gimbaled engine mounting. The engine is mounted so that its exhaust end is free to move and thus direct the exhaust gases in a desired direction. There are two serious objections to this method of control. All fuel lines must be flexible, and the control system that moves the engine must furnish considerable power.

The gimbaled engine mounting does not give full control about all three axes. It cannot control roll. To get control on all axes, two gimbal-mounted jets can be positioned as shown in figure 5A5. Both jets must be free to move in any direction, and each jet must respond to signals from any of the three control channels (pitch, roll, and yaw).

A control system using four jets is shown in figure 5A6. Each jet turns in only one plane. Two of the jets, Nos. 1 and 3, control yaw. Jets 2 and 4 control pitch, and all four jets are used together to control roll.

If the four jets can not provide enough thrust to propel the missile at the desired speed, a fifth jet, fixed in position, can be centered in the space between the movable jets.

Positions of the jets are controlled by hydraulic cylinders linked to the engine housing. One cylinder and linkage is required for each engine. The direction in which hydraulic pressure is applied is determined by an electric actuator.

FIXED STEERING JETS. Figure 5A7 shows a fixed jet steering system. The jets are placed around the missile so as to give directional control by exerting a force in one direction or another. A missile using this control

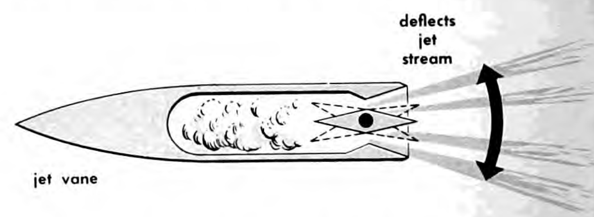


Figure 5A3.—Jet vane control

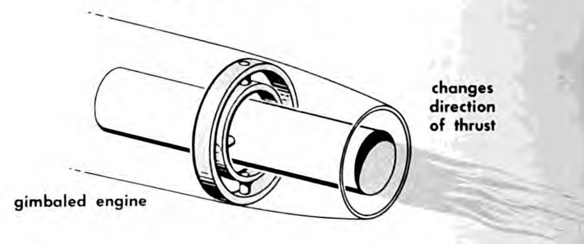


Figure 5A4.—Jet control of direction.

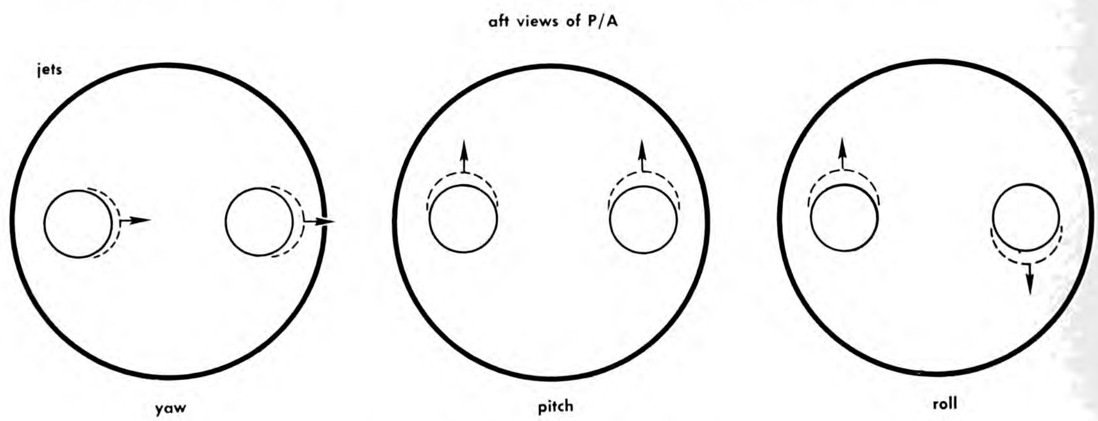


Figure 5A5.—Control by two jets.

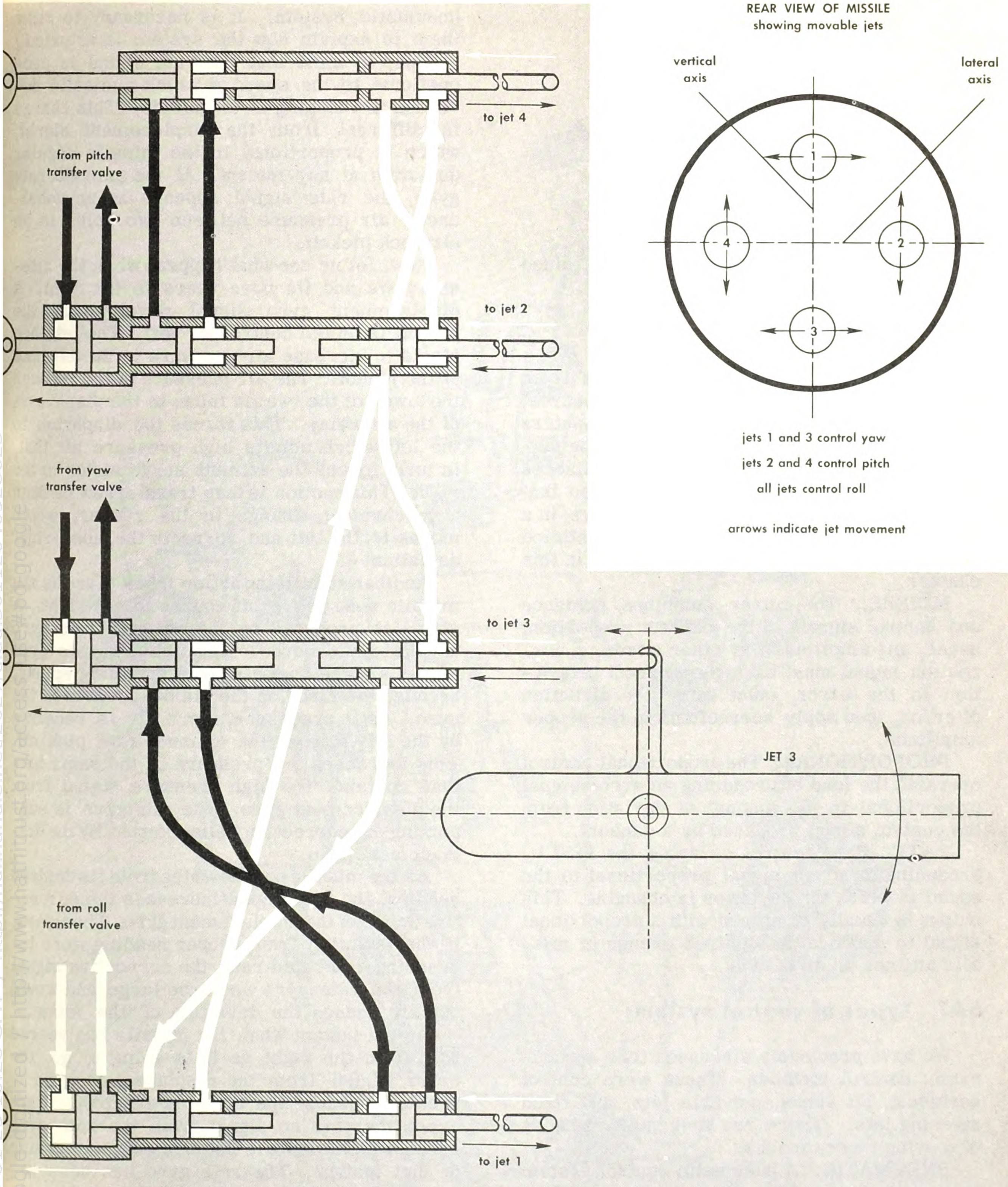


Figure 5A6.—Four movable jet control.

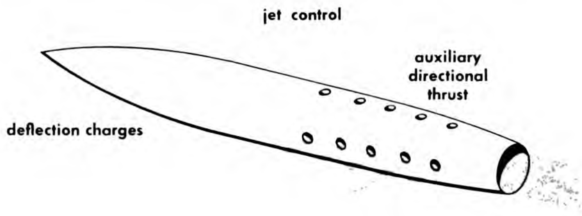


Figure 5A7.—Fixed jet steering.

system has a smooth outside surface, since control surfaces are eliminated.

5A6. Types of control action

The basic control signals may come from inside the missile, from an outside source, or both. To coordinate the signals, computers are used to mix, integrate, and rate the signal impulses. We will first briefly discuss individual computer section functions so that you may see the part the computer plays in a complete control system. A more detailed discussion of computers appears later in this chapter.

MIXERS. The mixer combines guidance and control signals in the correct proportion, sense, and amplitude. In other words, a correction signal must have the correct proportion to the error, must sense the direction of error, then apply corrections in the proper amplitude.

PROPORTIONAL. The proportional control operates the load by producing an error signal proportional to the amount of deviation from the control signal produced by a sensor.

RATE. Rate control operates the load by producing an error signal proportional to the speed at which the deviation is changing. This output is usually combined with a proportional signal to produce the desired change in missile attitude or direction.

5A7. Types of control systems

We have previously discussed four aerodynamic control methods. These were control surfaces, jet vanes, movable jets, and fixed steering jets. There are four basic methods of moving these devices.

PNEUMATIC. A pneumatic control system is shown in figure 5A8. (Some of the operating controls shown are not directly a part of the pneumatic system. It is necessary to show them to explain how the system is actuated.)

Keep in mind that the rate signal is proportional to the speed at which a missile deviation is changing in magnitude. This change is different from the displacement signal, which is proportional to the missile angular deviation at any instant. At the azimuth rate gyro, the rate signal appears as an unbalanced air pressure between two holes in an airblock pickoff.

Now, let us see what happens when the missile yaws and its nose veers to the right. A displacement gyro signal develops at the pickoff (azimuth control air jet). The jet then pivots to increase air pressure in the left hole of the pickoff. The air pressure is fed through the lower of the two air tubes to the diaphragm of the air relay. This forces the diaphram to the left which admits high-pressure air that, in turn, forces the azimuth servo motor to the right. This motion is then transferred through a mechanical linkage to the rudder, which moves to the left and corrects the nose-right deviation.

Another stabilizing action takes place as the missile nose veers off course to the right. A signal is produced by the azimuth rate gyro as the nose moves. The azimuth rate gyro exerts a force on the right restraining spring, because the force on the gimbal precesses the gyro. As it precesses, more air is received by the left hole of the azimuth rate pick off. This increases the pressure in the same tube that contains the high pressure signal from the displacement gyro. The rate gyro is supporting the correction being exerted by the displacement gyro.

As the missile path deviates from its desired heading, the rate signal increases the corrective action of the displacement gyro. Therefore, if the deviation from proper heading were increasing at a rapid rate, the corrective signal from the rate gyro would be large and would quickly reduce the deviation of the missile.

At the instant when the missile has veered as far to the right as it is going to go, the error signal from the displacement gyro is greatest because the error is greatest. However, there is no signal from the rate gyro because the missile is not changing its heading at that instant. The rate gyro has been returned to its mid-position by the restraining springs.

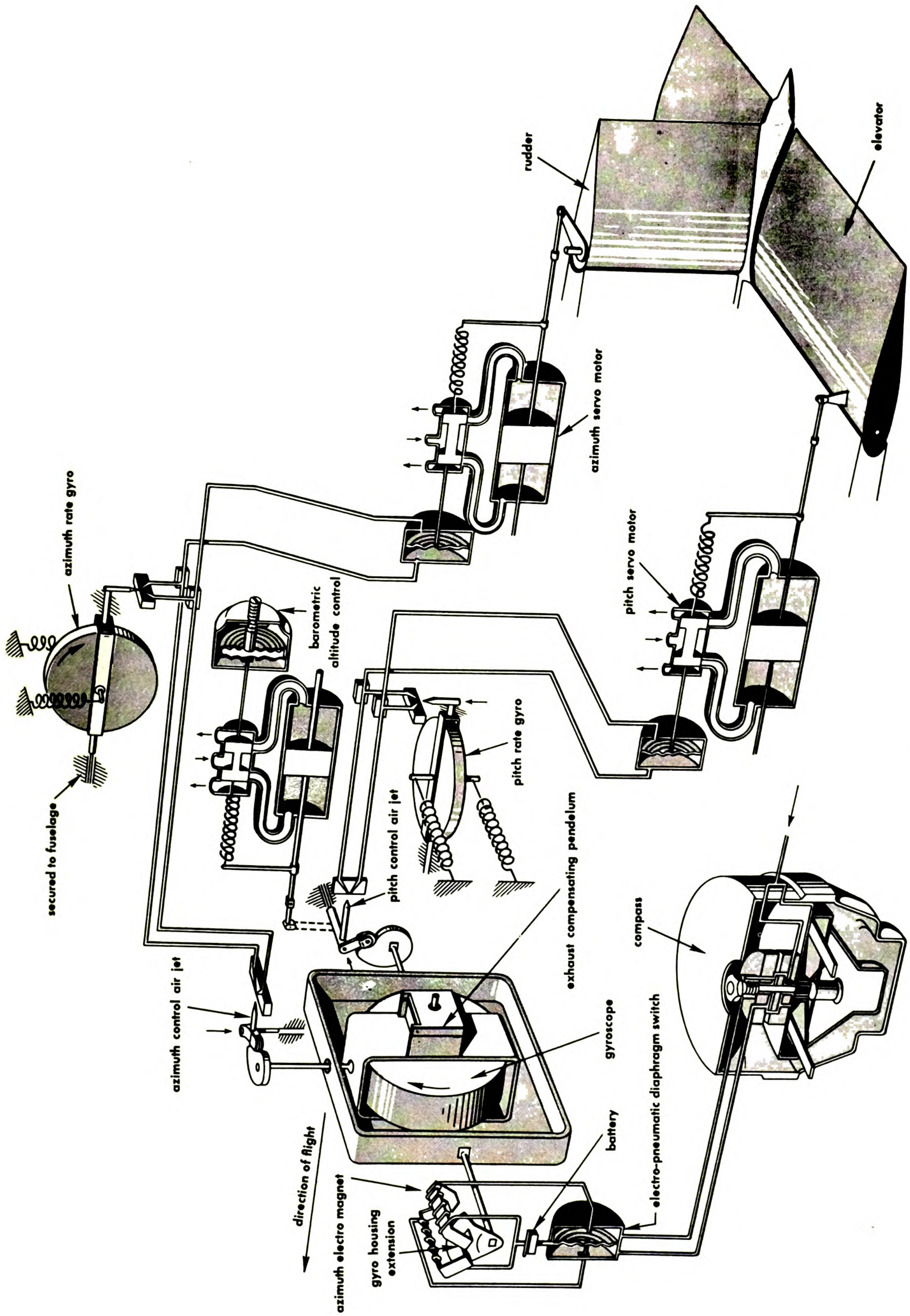


Figure 5A8.—Pneumatic control system.

An instant later the heading error is decreasing as the missile begins to correct its heading. The error from the displacement gyro still shows greatest pressure from the left hole of the azimuth pickoff because the heading error is still to the right. However, the signal is decreasing and the error signal from the rate gyro has reversed direction. The missile nose is now moving to the left. This puts a force on the rate gyro gimbal in a direction opposite to the former force. The precessing gyro creates a pressure in the right hole of the rate pickoff which is partially counteracted by the displacement gyro signal. Figure 5A9 shows the effects of combining the rate and displacement signals.

A study of this drawing will show the advantages of having a counteraction between the rate signal and the displacement signal. If the two signals were in the same direction, the rudder would be farther away from the center axis of the missile and the missile would be heading back to the desired course at a faster rate. However, the rate of return would be so rapid that the missile would swing past the correct heading in the opposite direction. The missile would then be veering off course to the left so that the control system would need correction signals for that direction.

The cross-course variations would continue, with the missile wobbling back and forth on both sides of the desired heading. This action is called oscillation, or hunting, and is very undesirable. The rate circuit action helps prevent hunting.

The same kind of action is used in the displacement and rate controls in the pitch channel. The fundamental rate gyro or rate circuit output is the same for all missile flight surface control systems.

PNEUMATIC-ELECTRIC. The pneumatic control system we have just described can be combined with other systems to refine the control action. Electric signal pickoff are accurate and dependable. They can provide a signal voltage that is proportional to displacement. They have a decided advantage over pneumatic systems in transporting information over wires, instead of through tubing.

It is difficult to design a small electric motor with sufficient speed and power to actuate missile flight control surfaces. But we can combine the best features of electric and pneumatic systems as in figure 5A10. Electrical equipment is used in the front end, and operates pneumatic servos at the actuating end. A system like that in figure 5A10 is suitable for controlling a small, subsonic, short-range missile.

Pneumatic controls are slow because air is compressible, and time is required to build up enough pressure in a cylinder to move the piston. Since the piston is linked mechanically to the flight control surfaces, there is a time

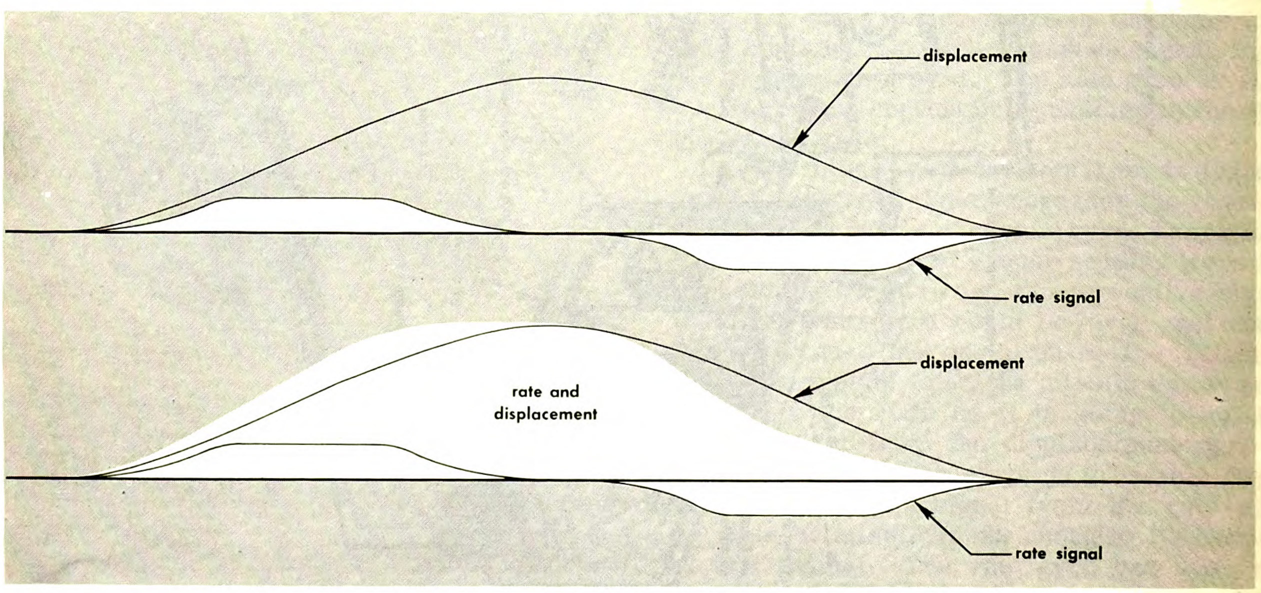


Figure 5A9.—Effect of combining rate and displacement signals.

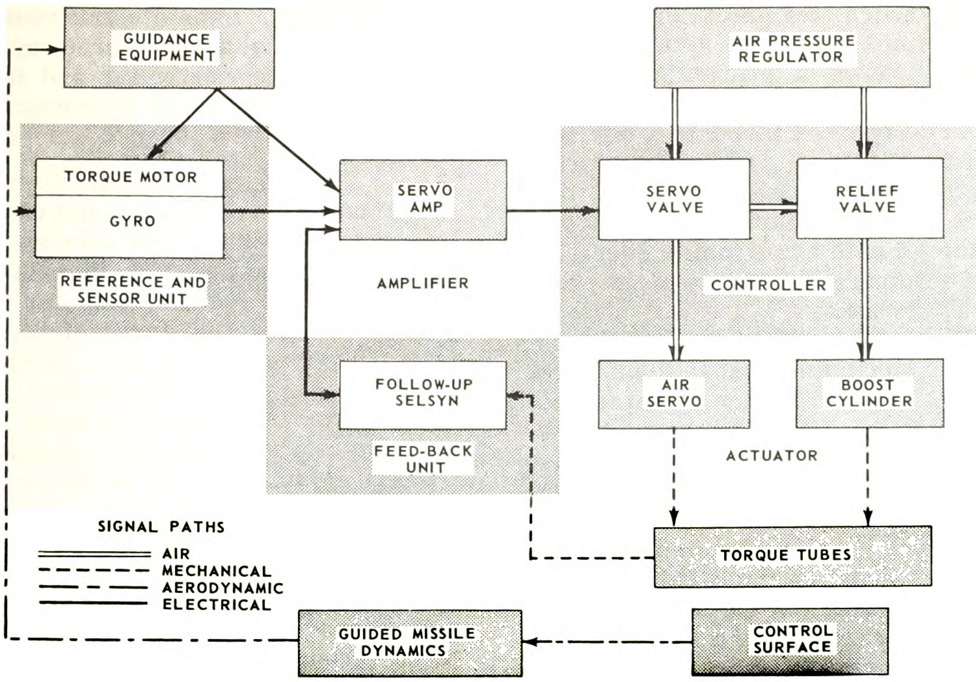


Figure 5A10.—Pneumatic-electric control systems.

lag between the control signal and the movement of the control surface. But the slow response can be speeded up by adding a booster cylinder, as shown in figure 5A10.

The increase in response speed is obtained by allowing air to escape, through ports, into a relief valve after the servo valve has moved a certain distance from midposition. The relief valve lets high-pressure air into the boost cylinder, which then acts in parallel with the actuator cylinder to move the flight control surfaces. The additional force provided by the boost cylinder makes it possible to obtain large control surface deflections in either direction.

The sensors for a pneumatic-electric system are electric pickoffs that detect gyro displacement and produce a voltage proportional to the heading deviation angle. This voltage is small, and must be amplified before it can operate a solenoid and air servo valve.

The change from electric to pneumatic operation takes place at the air servo valve. The air servo motor rotates the torque tubes which are connected to the control surfaces and extend into the center section of the missile. The system shown in figure 5A10 may be used for either pitch or azimuth control.

The servo amplifier receives a followup signal from the control surface, in addition to the gyro error signal. The voltage signal voltage is fed back with a polarity that opposes the input voltage. The feedback voltage cancels the control input voltage when the control surfaces have deflected a certain amount. The deflection of the control surfaces is therefore proportional to the input signal.

HYDRAULIC-ELECTRIC. This combination is similar to the pneumatic-electric, except that the actuators are moved by hydraulic fluid pressure instead of air pressure. This removes some of the disadvantages of a pneumatic system, since the fluid is not compressible.

In a hydraulic-electric system, a continuously operated pump maintains hydraulic pressure during the flight. The hydraulic fluid is circulated in a closed system, so that it can be used over and over. Thus the operating time of the hydraulic components is unlimited, and the system is suitable for long range missiles.

Variations in pitch, roll, and yaw are sensed by gyro reference units with electric pickoffs. The pickoff voltages are fed to amplifiers and computers and are then used to operate a controller. The controller is usually a hydraulic

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transfer valve, which regulates the amount and direction of fluid flow to the actuator.

Figure 5A11 shows a hydraulic-electric system for roll control. (In some missiles the ailerons are replaced by control devices called "rollerons".) The system uses proportional control only, which means that the controls react to information that shows the deviation of the missile axis from the desired flight path. The displacement signal is proportional to the deviation.

Should roll develop, the gyro (fig. 5A11) will detect it and cause the synchro to produce an error signal. The correction signal to the servo amplifier is the difference between the followup signal and the gyro signal, as indicated by the minus sign in the circle between the synchro block and the servo amplifier triangle.

The difference signal is amplified and used to operate the controller, which is a hydraulic transfer valve that regulates the flow of fluid to the cylinder. The piston in this cylinder operates the ailerons (rollerons; controllable jets; etc.) through mechanical linkages.

The equipment represented by the block labeled "jitter" provides an a-c voltage with a frequency of about 25 cycles per second. This is applied to the transfer valve and other equipment, to keep them in constant vibration and prevent the friction that may develop when the parts are not moving.

ELECTRIC. In an electric control system, all components are powered by electricity. Except for the controller and flight control surface actuator, the components are similar to those that have been described for other systems.

Variations in roll, pitch, and yaw are sensed by electrical components such as synchros or reluctance pickoffs. The signals from these components are fed to a computer which determines the amount of error, if any. Rate signals are obtained from the electrically driven rate gyro, or from an electric rate circuit operated by a displacement gyro signal. The control voltages are amplified and fed to controllers, which vary the power supplied to the motors that operate the flight control surfaces. A small motor running at high speed has the same power capability as a large motor running at low speed. Therefore a small, high-speed motor can be connected to the control surfaces through a reduction gear to secure the necessary torque.

A constant-speed motor, operating through a clutch, is best suited for rapid control operation, because the gear train inertia tends to cause an undesirable lag in control surface response. The lag may be great enough to make the missile oscillate about the desired trajectory. The use of a clutch helps to overcome this effect.

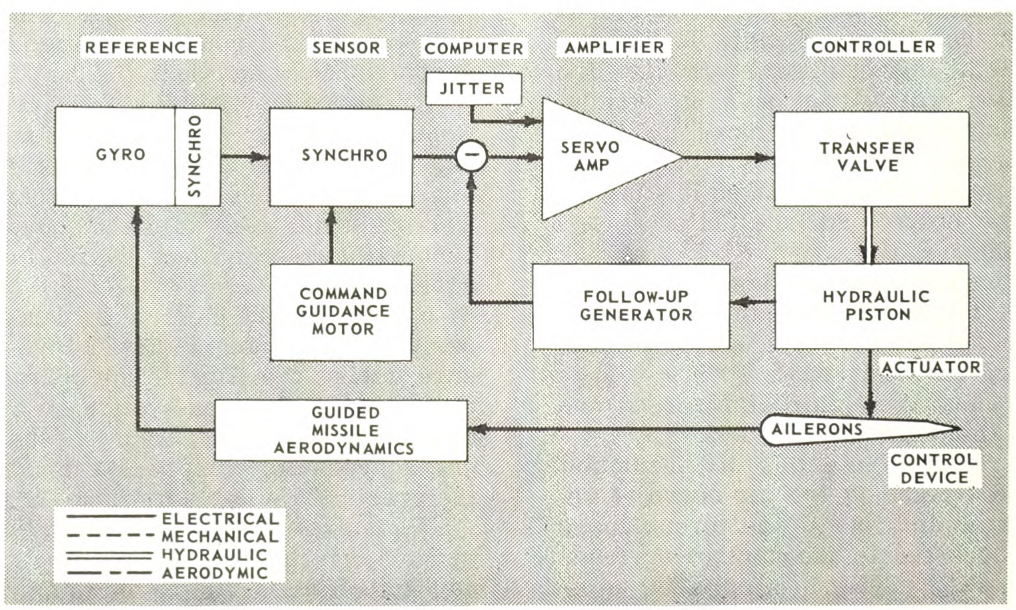

Figure 5A11.—Hydraulic-electric system for roll control.

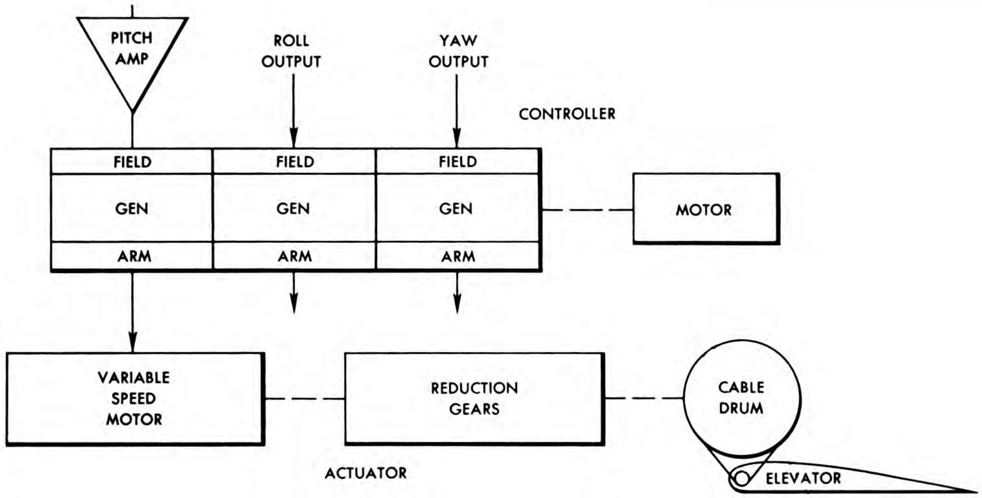

Figure 5A12.—Electrical system for pitch control.

An electrical system for pitch control is shown in figure 5A12. The controller section converts the power of the controller drive motor to power for the three-channel variable-speed motors. These motors operate when a signal is received from the amplifiers. Let us assume that the pitch amplifier furnishes a signal. This signal is applied in such a way that the magnetic field of the pitch generator is increased. This causes the generator to develop an output voltage, which is fed to the variable-speed motor. The shaft of the variable speed motor then begins to turn, putting an additional load on the controller drive motor.

The speed of the controller drive motor must remain reasonably constant, regardless of loading. Otherwise, if the pitch output decreases, the speed of the motor would decrease; this would result in decreased output from the roll and yaw generators at the same time. As a result, there would be undesirable cross-coupling between control channels so that the pitch signal would affect other channels, and vice versa.

5A8. Energy sources

The energy required to operate the control surfaces may be taken from any of the following sources.

MISSILE ENGINE. The propellant of the missile may be used as a source of energy to operate the control system. Figure 5A13 shows how a generator, a hydraulic pump, or a pneumatic pump may be mechanically connected to a turbo-jet or gas turbine engine. If a pump is used, it will provide the pressure needed for a hydraulic or pneumatic system. A power source of this type is practical even though some of the power developed by the engine is used to drive accessory equipment. There is ample power left for thrust.

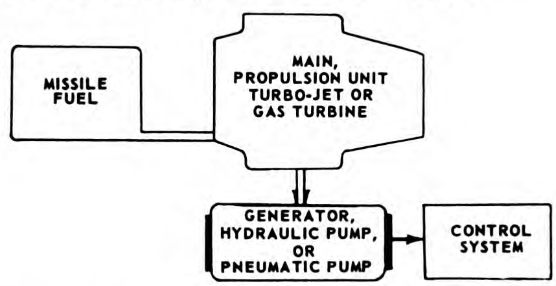

Figure 5A13.—How energy is obtained from the missile engine.

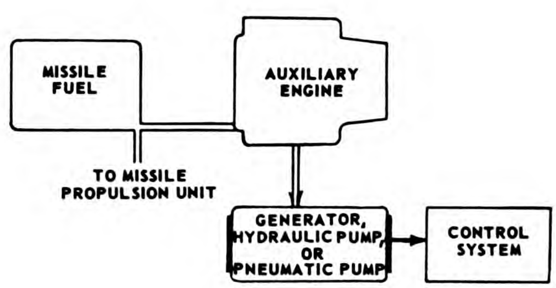

Figure 5A14.—Auxiliary engine power.

AUXILIARY ENGINE. A similar system, shown in figure 5A14, uses fuel from the main missile supply to drive a small engine, which in turn drives a generator for electric power or a pump for a pneumatic or hydraulic system.

This system does not take power from the main engine and would be suitable for use when the main propulsion unit was cut off. The auxiliary engine will furnish power so long as fuel is available. If necessary, the auxiliary engine could be used to drive a generator and pump simultaneously to obtain power for hydraulic-electric or penumatic-electric systems.

BATTERIES. Storage batteries can be used either by themselves or to drive motor-generator sets. The generator can supply electric power to operate a completely electric control system, or to drive pumps for combined control systems. Of course, batteries can supply large amounts of power for only short periods of time.

COMPRESSED GASES. Air and other gases can be stored in tanks under pressure for use in operating control systems. As explained in the section on pneumatic controls, the compressed gas is exhausted during the control operation and cannot be used again.

Turbine generators can be driven by the gases given off by BURNING FUEL CARTRIDGES if power is needed for a short time only. Such a power system is suitable for air-to-air missiles.

B. Requirements of a Missile-Control Servo System

5B1. General

Missile control is similar to any automatic control function. The system corrects some controllable quantity, and then checks the results as a basis for further corrections.

There are four requirements of any automatic control system. Obviously, the first is something to control. The second is a means of determining when any controllable item has departed from a desired condition. The third is a means of converting an error signal into a form that can be used to regulate the controlling device. The last is the device that performs the actual control operation.

5B2. Controllable factors

Factors that must be controlled by the missile control system are pitch, roll, and yaw. The system must provide a means of determining when the missile has departed from the desired attitude. Deviations are sensed by gyros. Electrical, mechanical, and electronic components are interconnected to form a complete control system.

The control system shown in figure 5B1 can set up fixed reference lines in space, from which deviations in attitude can be measured. It provides a mechanical and electrical means for operating the missile flight control

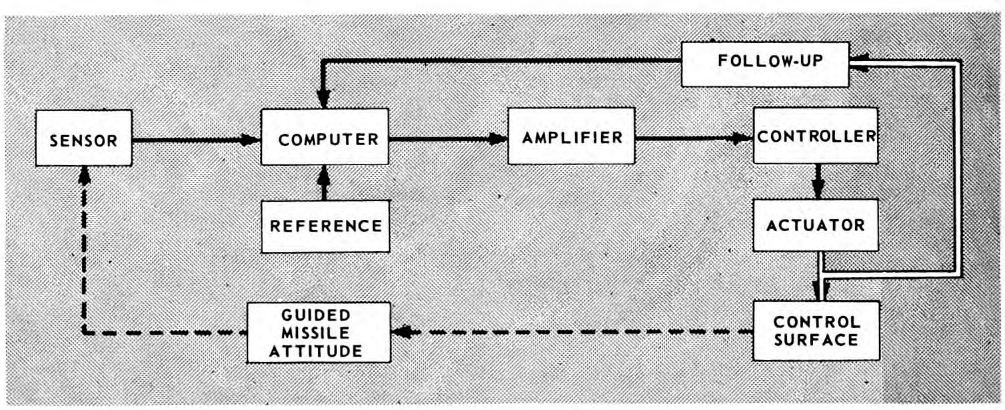

Figure 5B1.—Block diagram of missile control system.

surfaces, a means for measuring the magnitude and direction of errors, and a means for translating the error signals into control surface movement.

5B3. Error-sensing devices

Deviations in missile pitch, roll, and yaw are detected by gyros. A minimum of two gyros is necessary for missile flight stabilization. Each gyro sets up a fixed reference line from which deviations are measured. One such reference is the spin axis of a vertical gyroscope; from this axis deviations about the pitch and roll axes can be measured, as shown in figure 5B2.

A second reference line is the spin axis of a horizontal gyro, set up parallel to the horizontal axis of the missile as shown in figure 5B3.

Gyros used for missile control applications are divided into two classes: gyros used for stabilizing (control) purposes and gyros used for both guidance and stabilization. If turns or other maneuvers are necessary, a third gyro is required so that there will be one gyro for each sensing axis.

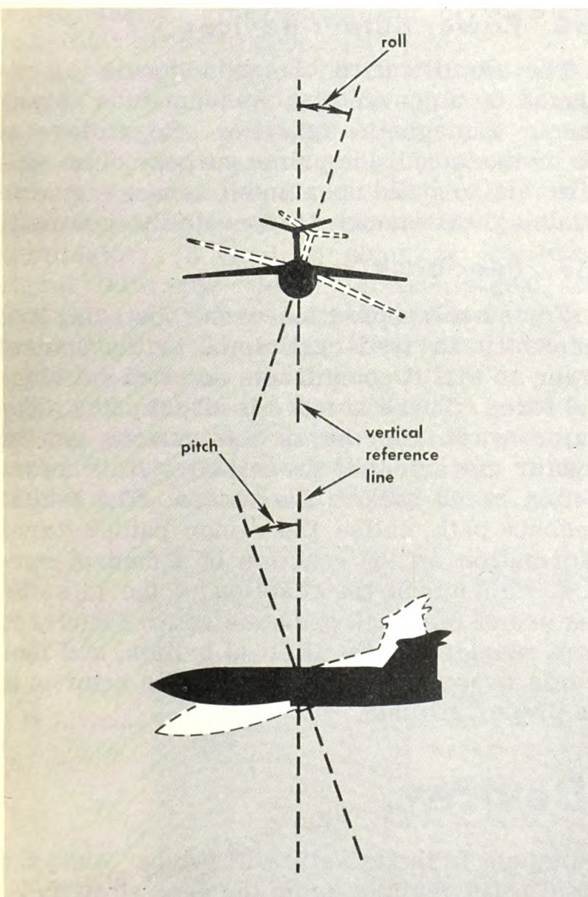

Figure 5B2.—Vertical reference line.

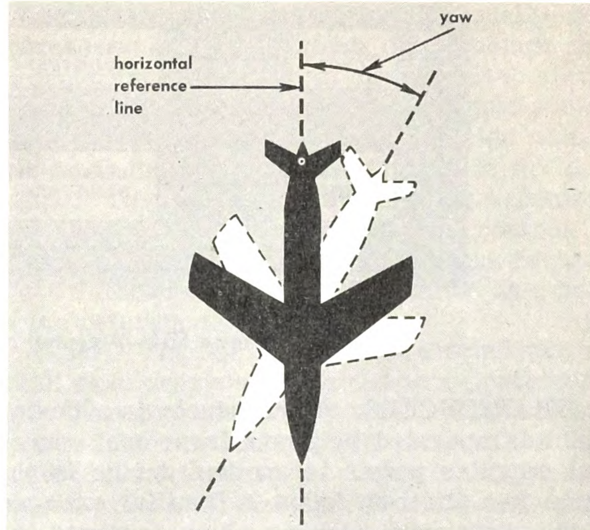

Figure 5B3.—Horizontal reference line.

In addition to the control signals from the vertical and horizontal gyros, which are proportional to the deviation of the missile from the desired trajectory, a signal that is proportional to the rate of deviation is required for accurate control and smooth operation. A RATE GYRO furnishes the rate of deviation signal.

A gyro that is being used for rate deviation indications has a restricted gimbal that is free to rotate about one axis only. The spin axis of a yaw rate gyro is mounted parallel to the missile line of flight. The roll rate gyro spin axis is parallel to the missile pitch axis, and at right angles to the line of flight. The pitch rate gyro spin axis is parallel to the yaw axis of the missile and at right angles to the line of flight.

Figure 5B4 shows, in block form, a system used to sense motion of a missile with respect to one control axis. This system uses both a rate gyro and a free gyro. The gyro output signals are fed to an amplifier, which adds them and gives an output voltage proportional to their sum. This voltage is applied to a servo motor, which positions the flight control surface so as to drive the error amplitude and the rate of change toward zero.

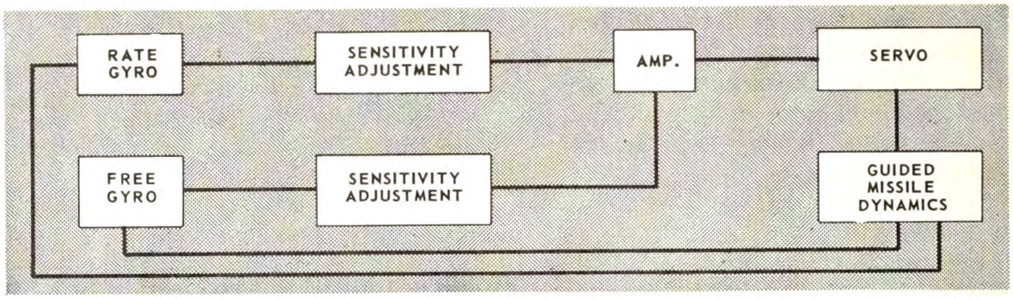

Figure 5B4.—A control channel using rate and free gyros.

TRANSDUCERS. A transducer is a device which is operated by power from one source and supplies power to another device in the same or a different form. A familiar example is the phonograph pick-up which converts the lateral motion of the needle in a record groove to electrical impulses which are then amplified. In most missile applications, a transducer is used in a similar manner—to change mechanical motion to an electrical voltage. More information on transducers will be given later in this chapter.

5B4. References

In order to accurately determine errors, the complete control system must have reference values built in. The system is then capable of sensing a change, comparing the change to a reference, determining the difference, then starting a process that will reduce the difference, to zero.

The reference units in a missile control system are of three kinds—voltage references, time references, and physical references. A more detailed discussion of references will appear in the next section of this chapter.

5B5. Correction-computing devices

We have shown that sensor units detect errors in pitch, roll, and yaw, and that a reference unit furnishes a signal for comparison with the sensor output.

Although the sensor output represents an error to be corrected, it is seldom used to operate control surfaces directly. It must be changed to include additional information, and then amplified in order to operate the controls. These operations are represented by the block labeled "computer" (fig. 5B1). The computer section is normally composed of mixers, integrators, and rate components.

5B6. Power output devices

The amplification of error signals is performed by a conventional vacuum-tube amplifier or a magnetic amplifier. Regardless of the method used, the prime purpose of an amplifier is to build up a small sensor signal to a value great enough to operate the controls.

5B7. Feedback loops

For smooth operation of the controls, it is necessary to feed back some of the control power so that it counteracts some of the original force. There are two feedback paths. The major path represents information on the angular movement of the missile. This information is fed back to the sensor. The second feedback path, called the minor path, returns information on the reaction of a control surface, rather than the reaction of the missile. The use of feedback prevents control surfaces from swinging to the limit of motion, and thus avoids overshooting as the missile returns to the proper attitude.

C. Reference Devices

5C1. Purpose and function

The reference device provides a signal for comparison with a sensor signal, so that equipment in the missile will "know" when the missile has deviated from the desired attitude. Figure 5C1 shows how the reference section is connected to the computer section. If the

reference section were omitted from the control section, the computer would be unable to set up correction signals.

5C2. Types of reference

In the following discussion, the three types of reference signals will be described separately to show how each type functions in the complete control system.

VOLTAGE. In some control systems, the ERROR SIGNALS are in the form of an a-c voltage which contains the two characteristics necessary to make proper corrections in the flight path. These are the amount of deviation, and the direction of sense of the deviation.

The amount of deviation may be indicated by the amplitude of the error signal so that, as the deviation increases, the amplitude increases; and if the deviation decreases, the amplitude decreases. Therefore, when the missile attitude has been corrected and there is no longer a deviation, the error signal amplitude drops to zero.

The direction of deviation may be carried by the a-c signal as a phase difference with respect to the phase of a reference signal. Only two phases are required to show direction of deviation about any one control axis. When a phase-sensitive circuit, such as a discriminator, is used to compare the error signal with the a-c reference signal, the direction of error is established and the output containing this information is fed to other control sections.

In most cases, the a-c reference voltage is the a-c power supply for the control system. It also furnishes the excitation voltage for the sensor unit that originates the error signal.

The controller unit (fig. 5C1) usually requires a d-c signal, which must include the information contained in the original error signal. The amplitude of the d-c signal shows the amount of deviation. The direction of deviation is indicated by the polarity of the d-c signal. To keep the d-c signal from becoming so large that it would cause overcontrol, a LIMITER CIRCUIT is used. Limiters require a d-c reference voltage, and function as a part of the reference unit.

TIME. The use of time as a reference is familiar to everyone. One common application is in the automatic home washer. A clock-type motor drives a shaft, which turns discs that operate electric contacts. These contacts close control circuits that operate hot- and cold-water valves, start and stop the water pump, change the washer speed, spin the clothes dry, and finally shut off the power. Each operation runs for a specified time interval. This kind of timer can be used for certain missile control operations.

Timer control units vary considerably in physical characteristics and operation. All of them require an initial, or triggering, pulse. Since all timers in a complete system are not triggered at the same time, each must have its own trigger. This is usually an electrical signal. It may be fed to a solenoid which mechanically triggers the timing device.

Another triggering method involves the application of an electrical signal to a heater coil which heats a bimetal strip and causes it to bend, thus opening or closing electrical contacts. This method may be more familiar when you contemplate the operation of a typical thermostat like the one found in the home. Still another triggering method is to apply an

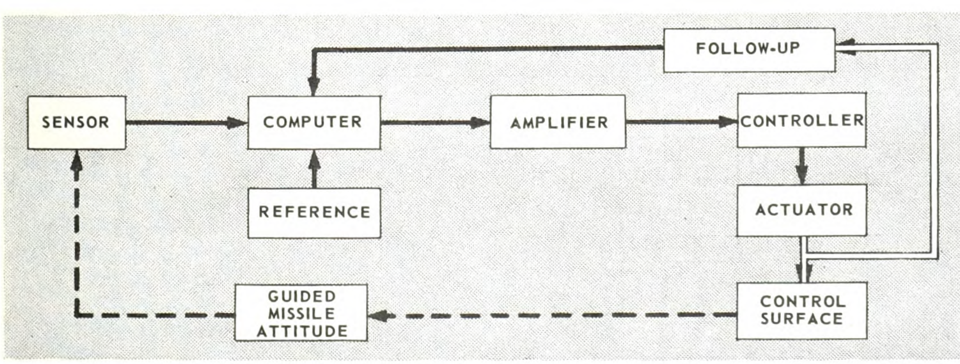

Figure 5C1.—Basic missile control system.

electrical signal to a motor. The motor, which is a part of a timing device, then starts the control sequence in much the same manner in a home washer.

Mechanical timers are used in some missile control systems. In operation, these timers are similar to mechanical alarm clocks. The energy is stored in a main spring. If a mechanical timer is used in a missile, the clock mechanism is not started until the missile is in flight, and therefore some form of triggering linkage is necessary. This usually consists of a catch that can be released by a solenoid. Since the spring cannot be rewound after the missile has been launched, a mechanical timer can be used only once during a flight.

Electrical timers in missile control systems are divided into motor types and thermal types. The triggering of either type is done by an electrical signal, and the time interval begins when the trigger voltage is applied. A simple motor timer is shown in figure 5C2. The speed of the motor shaft is reduced by the gear reduction box so that the output shaft revolves at the speed needed to time the operation.

An arm connected to the output shaft serves as part of a switch contact system. The length of time required for the arm to travel from the starting position to the point where contact is made is the delay time of the unit. Normally, this mechanism is used only once during a missile flight. If recycling is necessary, a more complex unit is required.

Thermal delay tubes and relays may also be used to control time delay actions. Thermal delay devices have the advantage over clock timers in that they can be made to recycle

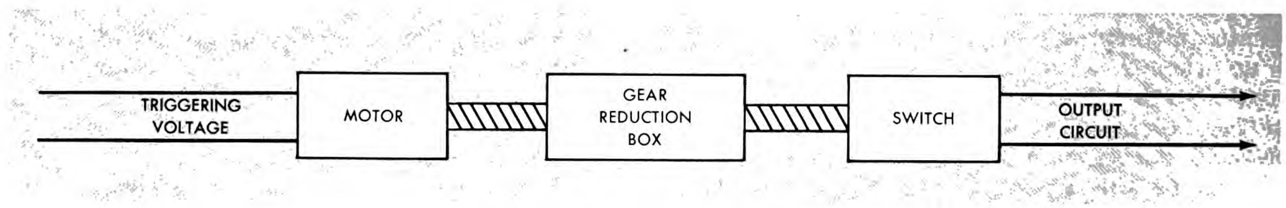

Figure 5C2.—Simple motor timer.

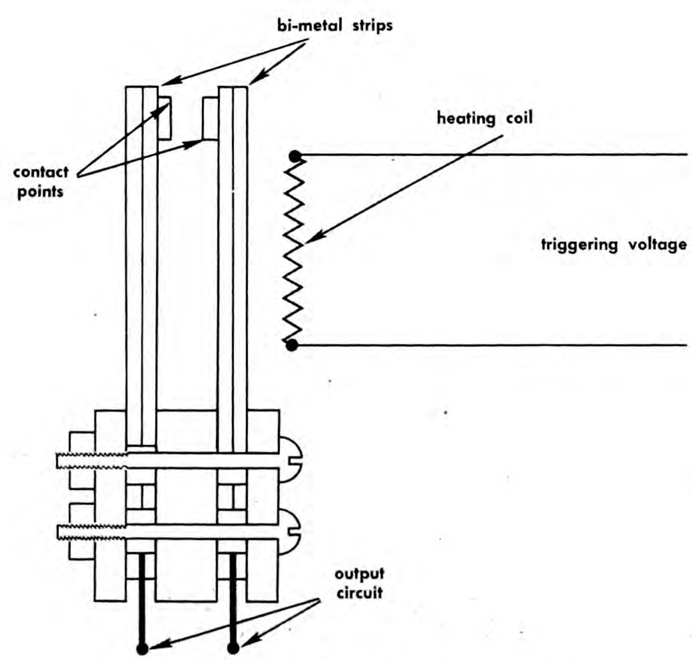

Figure 5C3.—Thermal delay tube.

without additional circuitry or mechanisms. However, they do not have the accuracy of clock timers.

One type of thermal delay tube is shown in figure 5C3. Its components are the two bimetal strips, the contacts, a heating coil, and the strip supports. When a triggering voltage is applied, the heating coil heats ONE of the bimetallic strips. As the temperature rises, the strip deforms and its contact moves toward the other contact. When the bimetal strip has heated sufficiently, the contacts touch and the output circuit is completed.

The amount of time between application of the triggering voltage and closing of the contacts is determined by the contact spacing, the temperature characteristics of the metals in the strips, and the characteristics of the heater coil. The delay time is preset by the manufacturer; the assembly is then placed in a tube-type enclosure, and the air is pumped out of the tube. This type of construction prevents any adjustment of the time delay.

The effect of ambient temperature variations can be avoided by making both strips of the same metals. Then, when one strip deforms because of outside temperature effects, the other strip deforms the same amount in the same direction. This maintains a more or less constant spacing between the contacts.

PNEUMATIC. Pneumatic timers may be used in certain missile applications. Time delay action is obtained by compressing air in a cylinder and then allowing the air to escape through a small orifice.

There are two general types of pneumatic timers—piston and diaphragm. The piston type is shown in figure 5C4. The felt washer acts as an air seal. As the plunger is pulled up, the spring is compressed and the contacts are opened. The spring is held in compression by the inertia block.

The inertia block forms the trigger for the timer. The block is of metal and will be thrown backward when it is subjected to sufficient accelerations. Thus, when a missile is launched, the block will fly back and release the catch that holds the spring under compression. Spring pressure will then push the piston downward, forcing air out through the orifice. The orifice opening may be changed by adjusting the needle valve. The smaller the orifice,

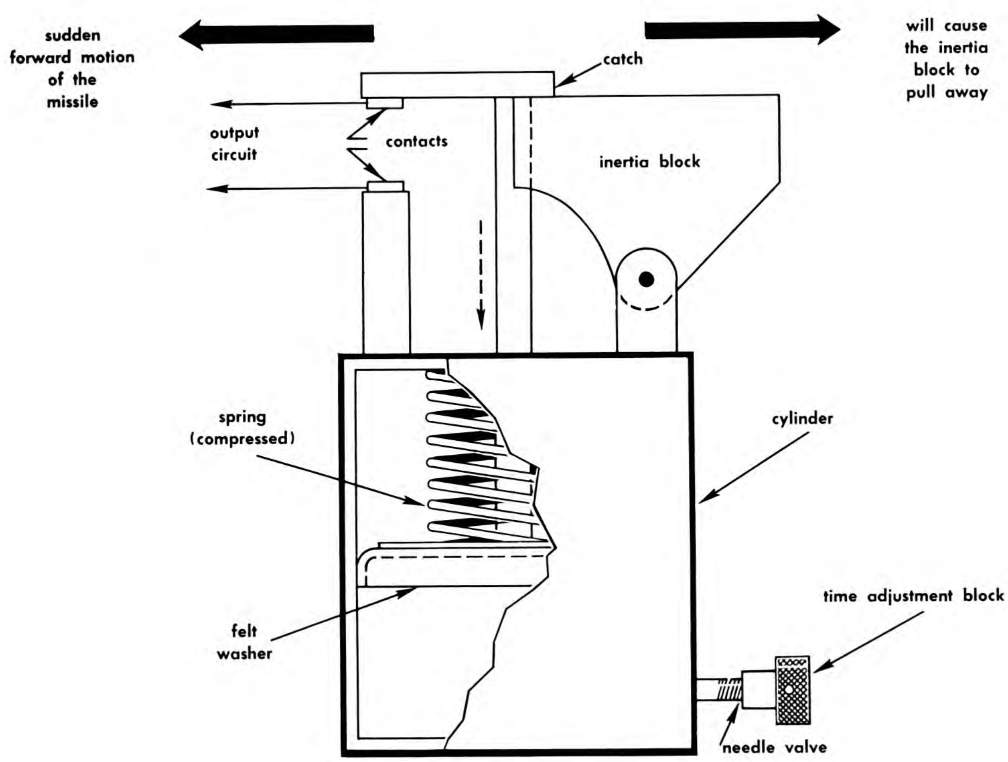

Figure 5C4.—Piston-type pneumatic timer.

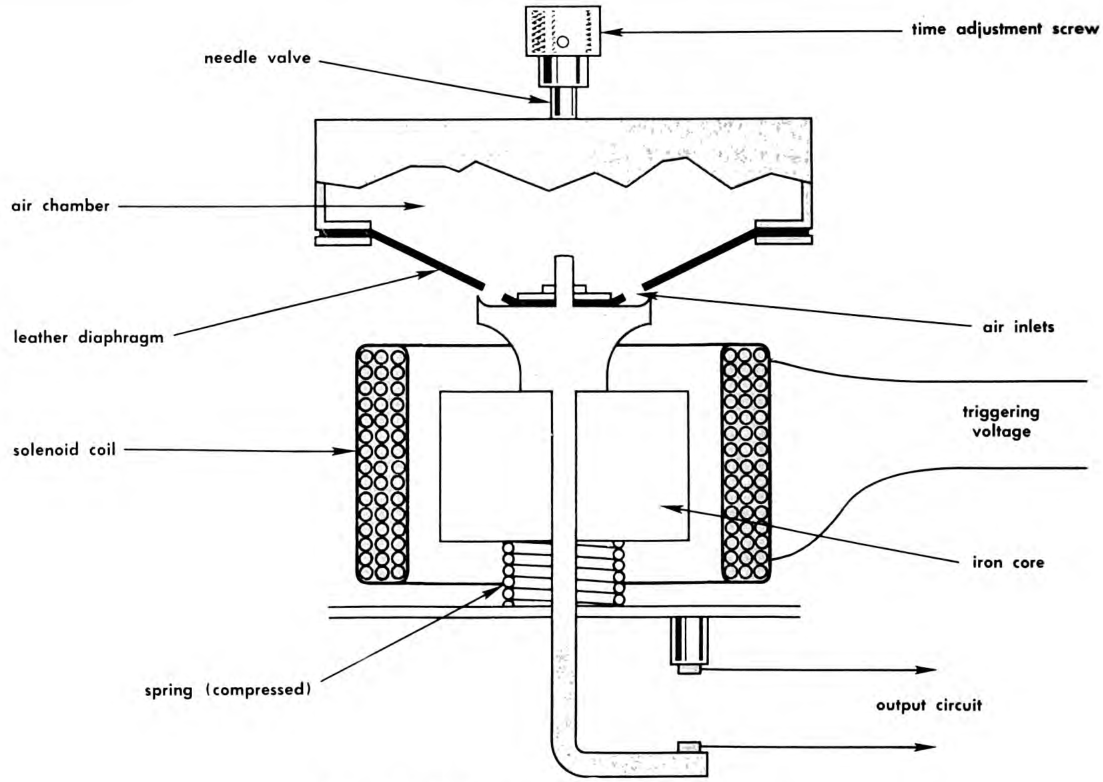

Figure 5C5.—Diaphram-type pneumatic timer.

the longer it will take the piston to come down far enough to close the contacts.

The diaphram-type pneumatic timer, shown in figure 5C5, operates on essentially the same principle as the piston-type timer that has been described.

Most missile control systems use some form of timer. Remember that an individual timer may be used to start a variety of control functions. Sometimes a timer is used strictly as a safety device.

PHYSICAL REFERENCES. There are a number of references for missile control systems other than the voltage and time classifications we have discussed. The remaining types have been grouped under the heading of physical references. They include gyros, pendulums, magnetic devices, and the missile airframes.

GYROS. We have already explained how a gyroscope establishes a reference line in space. A gyro pickoff system can sense any change in missile attitude with respect to that reference.

PENDULUM. The mass of the earth has a strong gravitational attraction for objects near its surface. If a weight is hung on a string and suspended from a beam or other support, the string and weight form a pendulum. The weight may swing around when it is first suspended, but it will eventually come to rest. The string will be on a line between the point of support and the earth's center of gravity. The pendulum can therefore be used to establish a vertical reference line.

Some gyros are precessed to a vertical position by a pendulum device called a "pendulous pick-off and erection system." The complete gyro system is called a vertical gyro; it may be used to measure the pitch and roll of a missile.

MAGNETIC DEVICES. Magnetic compasses have been used for centuries to navigate the seas. The compass enables a navigator to use the lines of flux of the earth's magnetic field as a reference. A similar device, known as a "flux valve" is used in some missile control systems. Its primary purpose is to keep a

directional gyro aligned with a given magnetic heading. The directional gyro can then be used to control the yaw of a missile.

MISSILE AIRFRAME. The airframe of the missile must be used for certain references. For example, the movement of flight control surfaces cannot be referenced to the vertical, or to a given heading, because such references change as the missile axes change. Therefore, movement of flight surfaces are referenced to the missile airframe.

Synchro indicators can be used to indicate the angular position of control surface with respect to the missile airframe. A potentiometer can be used in the same way by mounting in on the missile airframe so that its shaft will be driven by the flight control surface movements.

D. Sensor Units

5D1. General

The sensor unit in a guided missile control system is a device used to detect deviation from the desired attitude. In this section, we will discuss the use of gyroscopes, altimeters, and transducers as sensing units. Gyroscopes are generally considered to be the basic sensor unit in any missile control system. Other types of sensors, such as altimeters and transducers, are classed as secondary units.

5D2. Gyros

A gyroscope contains an accurately balanced rotor that spins on a central axis. Figure 5D1 shows a FREE GYRO that is mounted so it can tilt, or turn, in any direction about its center of gravity.

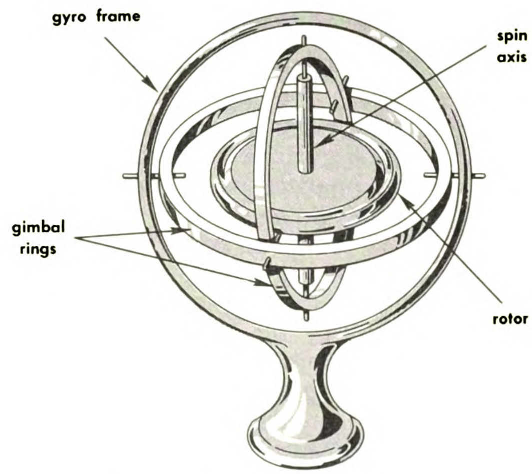

Figure 5D1.—Free gyroscope.

GYROSCOPIC INERTIA. The characteristic of a gyroscope that resists any force which tends to displace the rotor from its plane of rotation is called "gyroscopic inertia." Three factors determine the amount of inertia. These are: the weight of the rotor, the distribution of this weight, and the speed at which the rotor spins.

A gyro with a heavy rotor has more rigidity than one with a light rotor, if the speed of rotation is the same for both. Distributing the weight of the gyro to the outer rim of the rotor will give increased rigidity even though there is no increase in the weight of the rotor. An increase in gyro rigidity can also be obtained by increasing the speed of rotation.

PRECESSION, REAL AND APPARENT. The characteristic of a gyro that causes the rotor to be displaced in a direction 90 degrees from that of the applied force is called precession. There are two types of gyro precession: REAL and APPARENT. Real precession is sometimes called INDUCED PRECESSION.

The direction in which a gyro will precess, when an external force is applied, is shown in figure 5D2. A force applied to a gyro at its center of gravity does not tend to tilt the spin axis from its established position, and therefore does not cause precession. A spinning gyro can be moved in any direction without precession, if its axis can remain parallel to its original position in space. Therefore, the gyro can measure only those movements of the missile that tend to tilt or turn the gyro axis. Two gyros are needed for vertical and horizontal stabilization of missile flight. The spin axes of these gyros would be at right angles to each other.

APPARENT PRECESSION. The axis of a spinning gyro points in a fixed direction

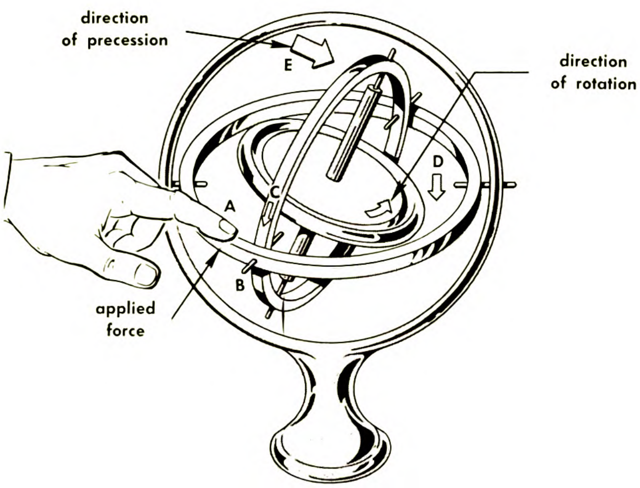

Figure 5D2.—Gyro precession.

because inertia fixes it in space. Over a period of time a gyro axis will appear to tilt. This is called apparent precession, and is due to the rotation of the earth.

Figure 5D3 represents a gyro at the equator, with the spin axis horizontal and pointed east-west. The earth turns in the direction shown by the arrow. If you could observe the gyro spin axis from a point out in space, it would appear to always point east. To an observer standing on earth, the spin axis appears to gradually tilt or drift, so that after three hours, the spin axis has tilted 45 degrees. Notice the apparent precession shown in figure 5D4. After 12 hours the spin axis is again horizontal, but is pointing west instead of east. At the end of 24 hours, the spin axis is pointing east again.

This action gives the impression that the gyro has turned end for end, and that a complete revolution is made every 24 hours. But this is not true. Actually, the gyro axis has maintained its fixed direction in space; only the earth has moved.

The apparent precession of a gyro makes it unfit for use as a reference over an extended time unless some kind of compensation is used to keep the gyro in a fixed relation to the earth's surface.

GYRO DRIFT. Gyro error caused by random inaccuracies in the system is called drift. It has three principal causes—unbalance, bearing friction, and gimbal inertia.

Dynamic unbalance may occur because of operation at some speed or temperature other than for which the gyro was designed. Some unbalance exists in any gyro because of manufacturing tolerances.

An even amount of bearing friction all around a shaft does not cause drift. It will, however, cause the speed of rotation to change.

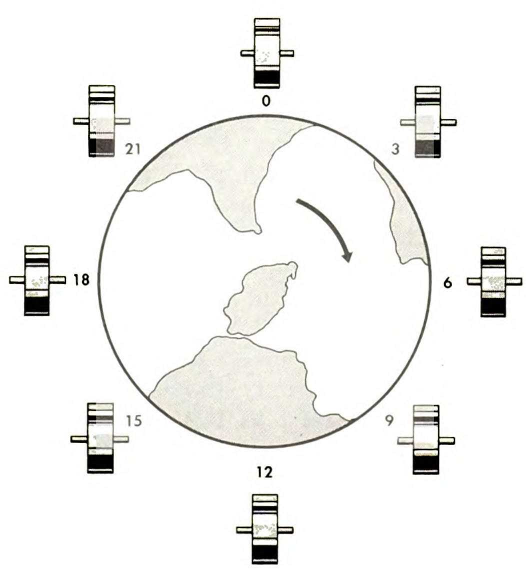

Figure 5D3.—Gyro position in space about the earth.

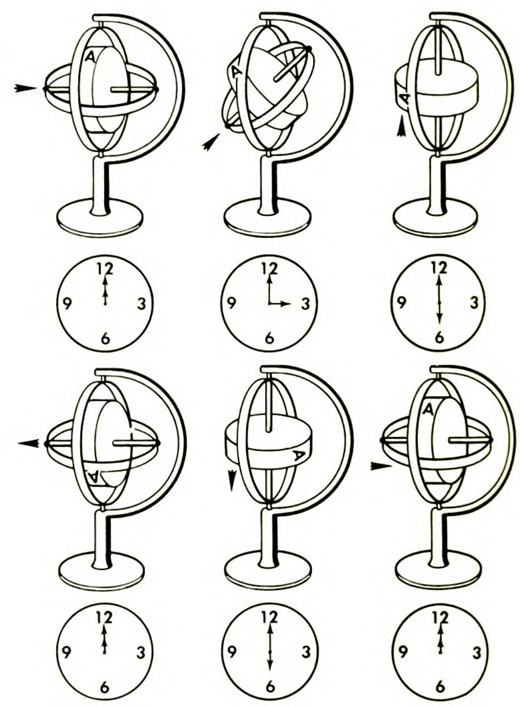

Figure 5D4.—Apparent precession.

Friction in the gimbal bearings causes a loss of energy and incorrect gimbal positions. Drift will be caused by friction in the spin axis bearings only if the friction is not symmetrical.

Energy is lost whenever a gimbal rotates, because of inertia. The larger the mass of the gimbal, the greater the drift from this source.

MOUNTING SYSTEMS. The main cause of random drift in gyros is friction in gimbal bearings. Figure 5D5 shows one type of mounting that has been developed to reduce this friction. It is called FLOATED GYRO UNIT.

The floated gyro unit is a viscous-damped, single-degree-of-freedom gyro with a microsyn torque generator and a microsyn signal generator mounted on its output shaft. The microsyn torque generator places a torque on the gyro gimbal.

The term "single-degree-of-freedom" means the gimbal is free to rotate with respect to the gyro case about a single axis. This axis is called the output axis; it is perpendicular to the gyro spin (reference) axis. If an angular velocity acts on the gyro case with a component about the input axis, a precessional torque develops about the output axis.

In figure 5D5 the gyro wheel is contained within the damper housing. The microsyn signal generator units are mounted on the gyro shaft as shown in the drawing. The space between the damper housing and the gyro case is filled with a viscous damping fluid. Because of the high specific gravity of the fluid, it serves to float the gyro damper housing and gyro gimbal shaft, and thus reduces the gimbal bearing friction and drift. Thermostatically controlled heaters around the damping fluid space keep the fluid viscosity constant. If the gyro shown in figure 5D5 were mounted with its input axis parallel to the pitch of yaw axis of the missile, the torque applied to the output shaft would be proportional to the difference between the desired angular velocity of the missile and its angular velocity about the axis.

Another form of gyro support, shown in figure 5D6, is known as an air bearing. This type of support reduces friction to such a low value that for all practical purposes it can be

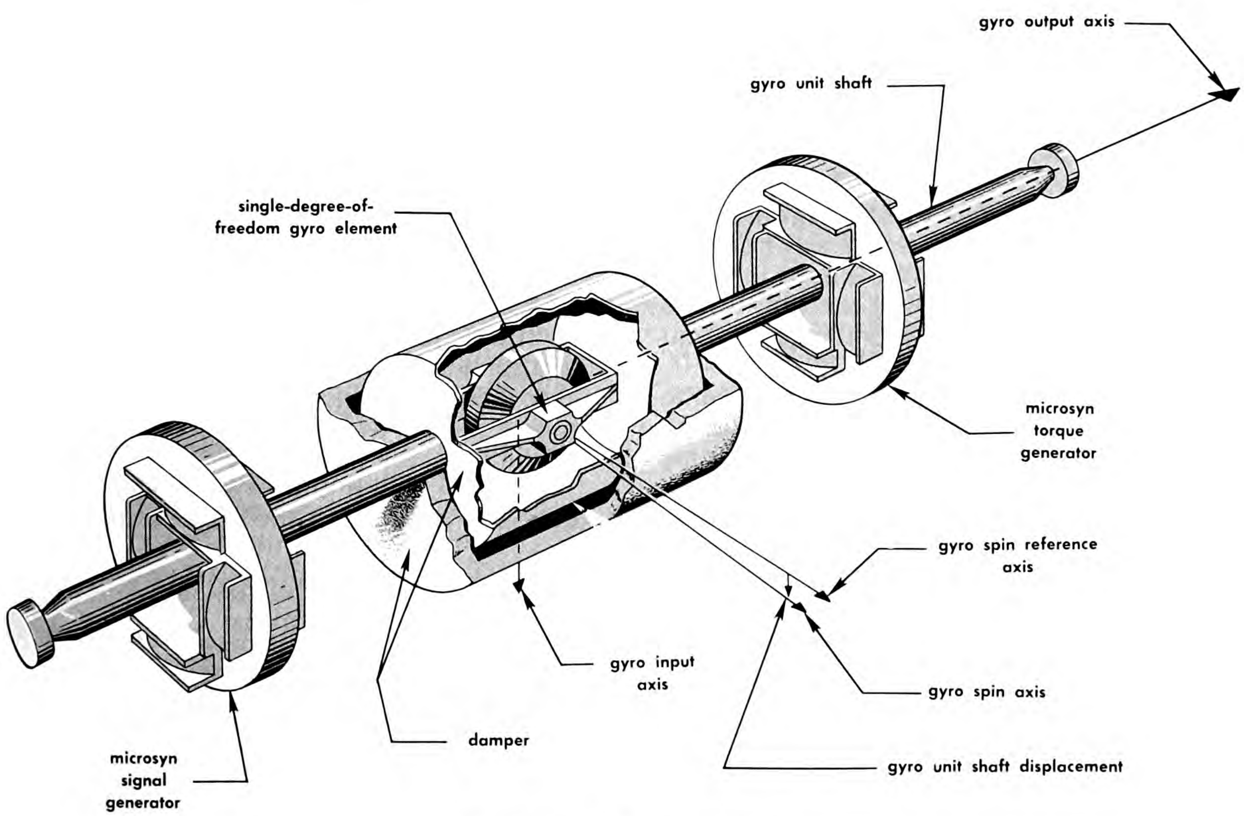

Figure 5D5.—Floated gyro unit.

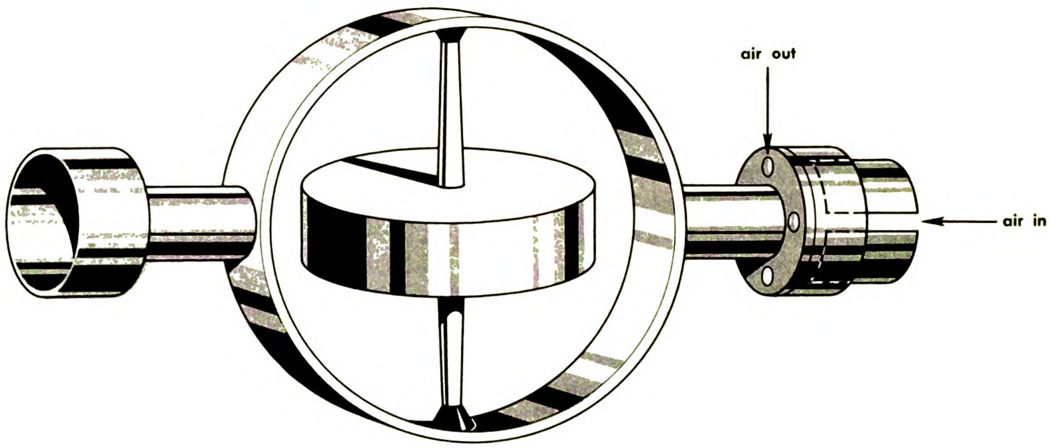

Figure 5D6.—Air bearing gyro.

considered zero. Its operating principle may be explained by using a fairly common advertizing display for comparison. No doubt you have seen vacuum cleaner displays where the air stream from the cleaner was used to keep a number of ping pong balls or a large rubber ball virtually suspended in the air.

ERECTING SYSTEMS. Figure 5D7 is a block diagram that shows how signals from a precession sensor are used to maintain gyro stability. If the gyro spin axis in this system is vertical, the gyro output signal will be zero. If the spin axis moves away from the vertical, the gyro will send a voltage to the precession sensor. The amplitude of this voltage will depend on the amount of precession, and its phase of the direction of precession. The precession sensor output is amplified to operate the torque motor, which returns the gyro to the vertical position.

Horizontal gyros use a leveling system to keep the spin axis horizontal, and a slaving system to stabilize its direction. The slaving system uses a flux valve to sense the direction of the earth's magnetic field. The flux valve unit is suspended on a universal joint enclosed in a bowl filled with fluid, to prevent excessive swinging in flight.

The gyro's spin axis, kept tangent to the earth's surface and slaved to the earth's magnetic field, provides a basic reference for missile heading. When the missile turns in either direction, the flux valve turns with it. When the flux valve turns, the angle between its coils and the earth's magnetic field is changed, and an error signal is generated. The error signal is amplified and used to operate controls that correct the missile heading.

RATE GYROS. The control signals furnished by the vertical and horizontal (free) gyros are proportional to the deviation of the missile. Another signal, proportional to the RATE of deviation, is required for smooth control. This is the RATE-OF-DEVIATION signal; it is supplied by a RATE gyro. A rate gyro has a restricted gimbal that is free to rotate about only one axis. Its construction is shown in figure 5D8.

A YAW RATE GYRO is mounted with its spin axis parallel to the missile line of flight.

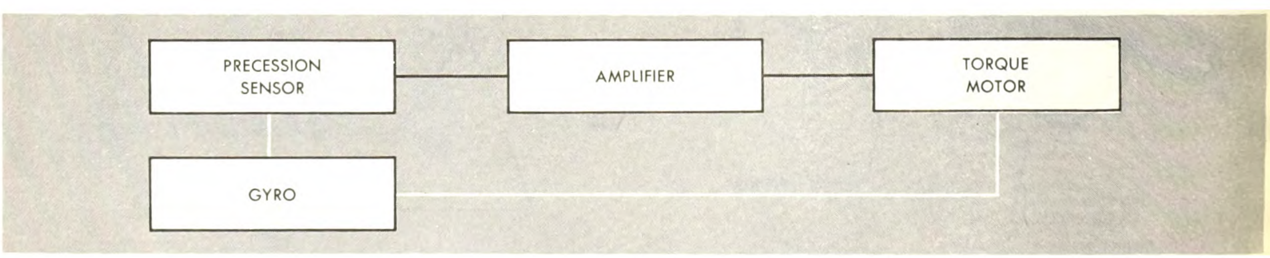

Figure 5D7.—Vertical gyro erection system.

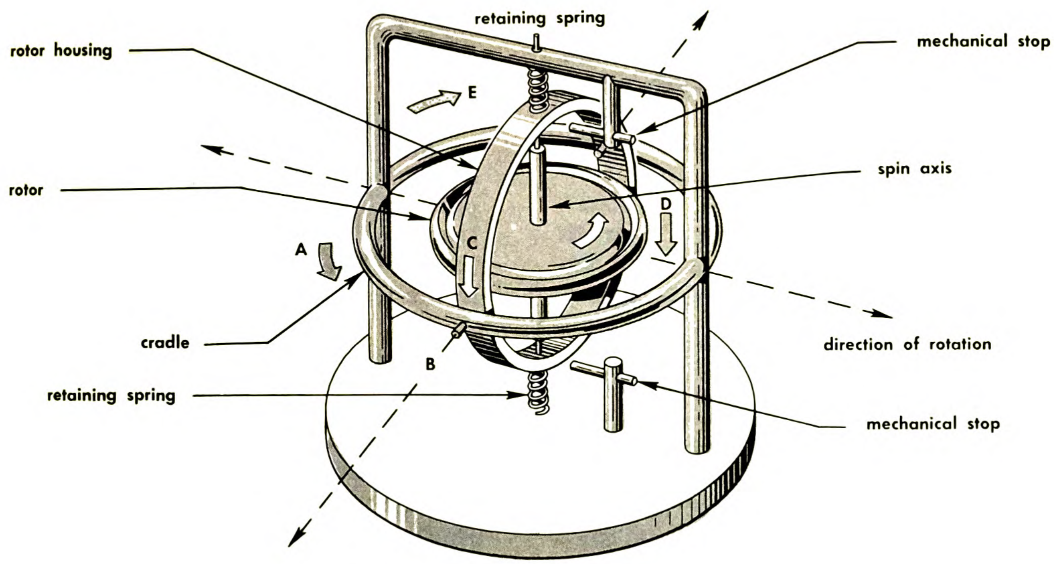

Figure 5D8.–Basic rate gyro.

A ROLL RATE GYRO is mounted so that its spin axis is parallel to the pitch axis, at right angles to the line of flight. A PITCH RATE GYRO is mounted with its spin axis parallel to the yaw axis of the missile and at right angles to the line of flight.

Displacement signals alone would give the missile a tendency to over-correct its errors, and yaw or pitch about its desired course. The displacement and rate of change signals minimize over-correction, and ensure stability.

PICKOFF SYSTEMS. A "pickoff" is a device that produces a useful signal from the intelligence developed by a sensor. The sensing devices for missile control generally indicate angular or linear displacement, measured with respect to some fixed quantity. The pickoff must be able to measure the amplitude and direction of the sensor displacement, and produce a signal that represents both quantities. Electrical pickoffs use phase relation or polarity difference to indicate direction. The ideal pickoff should have a linear output and minimum friction loss.

5D3. Altimeters

An altimeter measures altitude. There are two main types: PRESSURE and ABSOLUTE.

The PRESSURE type operates on the principle that air (atmospheric) pressure is greatest at sea level and decreases steadily as the altitude increases. Since the atmospheric pressure at a given altitude is predictable, it is possible to calibrate a pressure-sensitive instrument in terms of altitude.

A pressure altimeter is a form of aneroid barometer. Its mechanism includes a bellows-like chamber from which most of the air has been removed. The pressure of the atmosphere tends to collapse the bellows. The surface of the bellows is connected to a scale pointer through a mechanical linkage, which magnifies the bellows surface movement.

As the pressure does not remain constant at any one level, this type of altimeter may have an error due to variable atmospheric conditions.

The ABSOLUTE altimeter is sometimes called a radio altimeter. It indicates altitude above the ground, rather than above sea level. It is actually a form of radar, since it measures the time required for a radio pulse to reach the ground, be reflected, and return.

The transmitter antenna sends an FM signal straight down. The reflected energy is picked up by a separate antenna. A detector combines the reflected signal with a sample of the transmitted signal and generates a difference frequency. This frequency is determined by the height above the ground. The detector output is amplified and fed to an indicator such

as a cathode-ray tube, a meter, or a discriminator that operates a control circuit.

This system accurately indicates height above the ground, but it can not indicate height above sea level.

5D4. Air-speed transducers

A guided missile may use a transducer to measure ram air pressure, and provide an output voltage that indicates missile air speed.

One type of airspeed transducer uses bellows coupled to the shaft of a potentiometer. As the bellows is actuated by ram air pressure, it turns the potentiometer shaft and thus changes the circuit resistance.

Another type of airspeed transducer uses a synchro generator. The rotor of the synchro is so connected that expansion or contraction of the bellows causes the rotor to turn. This type of sensor will be described in the following section.

E. Pickoffs

5E1. Function

The pickoff device is important to the missile control system because it produces a signal from the intelligence developed by a sensor unit.

5E2. Requirements

The signal produced by the pickoff must be suitable for use in the control system it is serving. The pickoff must have an output sense. That is, it must be able to determine the direction of displacement and then produce a signal that indicates the direction. In electrical systems the indication may be a phase or polarity difference.

The ideal pickoff should have a considerable change in output for a small movement of the pickoff. It should also have minimum torque or friction loss since these losses would be reflected to the sensor element and affect its operation. Small physical dimensions and light weight are additional requirements for pickoffs used in missiles. The null point (no output) should be sharply defined.

5E3. Type

Electrical pickoffs in common use fall into four categories. Each has some characteristic that makes it suitable for certain applications.

SYNCHRO PICKOFFS. A synchro pickoff device is normally composed of a pair of synchro units wired as a generator and synchro motor. When an exciter voltage is connected to the pair, movement of the generator rotor will produce a corresponding movement of the synchro motor rotor. The generator rotor shaft can be turned by a mechanical connection to the sensor unit, or by a motor. Regardless of the method used to turn the generator shaft, the synchro motor shaft will move the same amount. The synchro motor does not develop enough power to operate missile flight control surfaces. Therefore, it is used to operate other parts of the system which in turn operate the control surfaces.

To get better action as the null point is approached, a differential synchro system is sometimes used. In this system, two inputs—one electrical and the other mechanical—are fed to a synchro differential generator unit, which then furnishes a voltage equal to the sum or difference between the two inputs.

Synchro pickoffs are sometimes called selsyns, autosyns, or microsyns.

POTENTIOMETERS. A potentiometer is a variable resistance that is normally used as a voltage divider. The resistance element is formed into a circular shape and a moving arm makes contact with the element. By connecting leads to the ends of the strip from a voltage supply and then connecting a load to the moving arm and one end of the strip, the source voltage may be divided by varying the position of the arm on the strip.

The resistance used for many electronic applications is composed of a thin film of carbon deposited on an insulating material. This type of resistance element is not suitable for servo applications because the resistance changes with temperature, humidity and wear. These disadvantages are overcome by using a wire-wound resistance strip, as shown in figure 5E1.

Figure 5E2 shows how a potentiometer divides voltage. The source voltage is applied

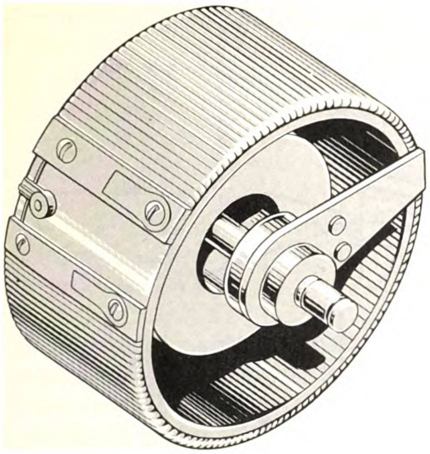

Figure 5E1.—Wire-wound potentiometer.

to points A and B. One side of the load is also connected to B. The section of the resistance strip between the moving arm and A acts as a resistance in series with the load, and there is less voltage at the load that is being furnished by the source. If the moving arm is all the way down to B, the load will get no voltage.

Thus, the position of the moving arm determines the amount of voltage. It is also possible to use the variation in resistance as a control medium. Since the resistance between A and the moving arm and between B and the moving arm vary as the arm is moved, a null can be indicated when the two resistances are equal.

If the shaft of the potentiometer is mechanically coupled to the sensor, the output voltage will vary according to the moving arm displacement. However, the voltage does not change smoothly with this type construction. The jumpy output is due to the voltage difference between adjacent turns of wire. In order to remove this objection, the resistance element is sometimes wound in the form of a helix. Units using this construction are usually identified by the name HELIPOT instead of potentiometer.

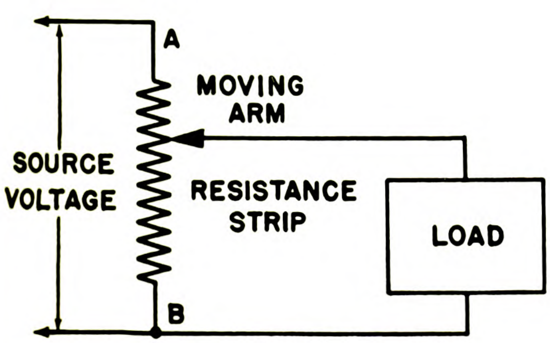

Figure 5E2.—How a potentiometer divides voltage.

Potentiometers are often used in bridge circuits. The potentiometer forms two arms of the bridge, and fixed resistors form the other two. It is also possible to use two potentiometers to comprise all four arms of the bridge.

RELUCTANCE PICKOFF. A variable reluctance pickoff and gyro rotor are shown in figure 5E3. (The gyro rotor is the cylindrical object in the drawing.) The rotor is made of ferrous material, which has been slotted lengthwise and the slots filled with brass.

The pickoff element is an E-shaped metal mass, of which the center arm is a permanent Alnico (special alloy of aluminum, nickle, and cobalt) magnet. The outer arms, and the long side of the E, are made of soft iron. Coils are wound on each leg and connected in series opposition. As the gyro rotates, it causes regular variations in the magnetic flux paths as the brass and ferrous strips pass the end pieces. This establishes regular variations in flux density and induces an a-c voltage in the coils. However, because of the opposing connection of the coils, the induced voltages cancel.

The gyro spin and precession axes are shown by dashed lines. As the rotor precesses, the air gaps at each end vary oppositely (one increases and the other decreases) in proportion to the precessing force, and cause different induced voltages in the pickoff coils. Since the two voltages are different they no longer cancel, and the output voltage is that produced by acceleration. The output voltage is rectified by the crystal diode and filtered by the condenser. The resulting d-c voltage can be used as an acceleration signal. The polarity of the signal voltage depends upon which coil has the greatest induced voltage, and therefore indicates the direction of the acceleration.

Figure 5E4 shows another type of reluctance pickoff. The stator has four coils divided into two pairs. One pair is supplied with a constant-amplitude a-c voltage from a reference oscillator.

Voltage from one pair of coils is induced in the second pair through an armature. The

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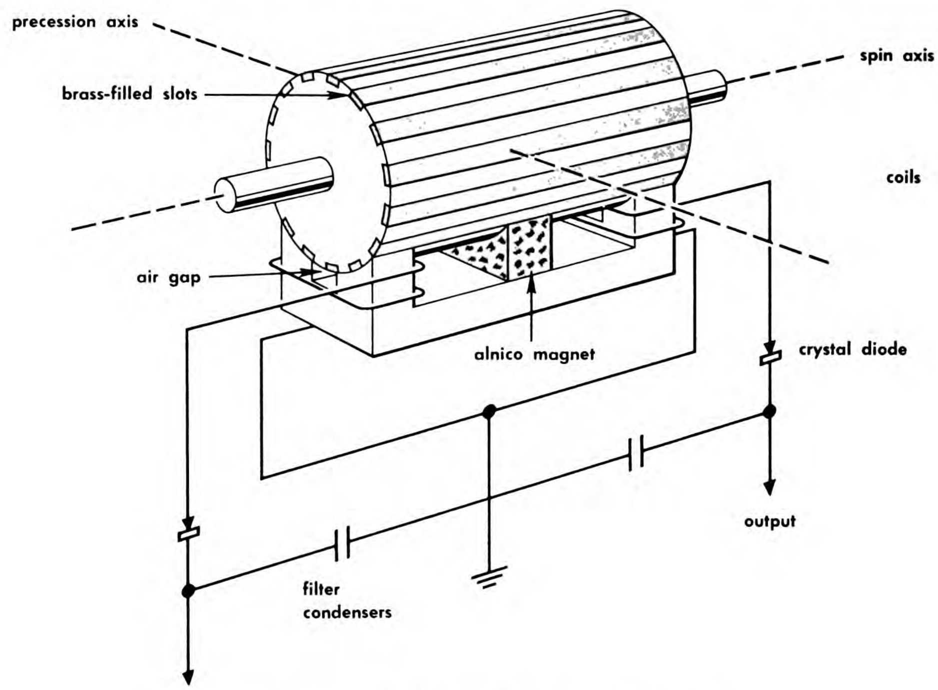

Figure 5E3.—Gyro rotor and reluctance pickoff.

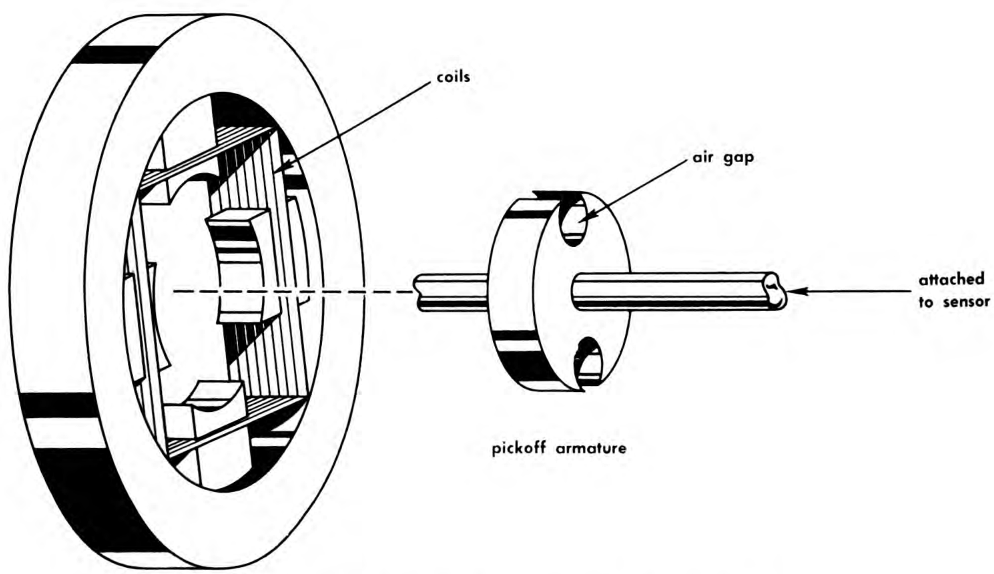

Figure 5E4.—Externally operated reluctance pickoff.

armature is fastened to a shaft that is mechanically coupled to the gyroscope gimbal. As the gimbal moves, it causes the armature position to change, and alters the coupling between the two sets of coils. The amplitude of the induced voltage changes in proportion to the gimbal movement. This change produces a phase shift that depends on the direction of shift in missile position.

CAPACITANCE PICKOFF. As shown in figure 5E5, a capacitance pickoff is composed of two outer plates that are fixed in position.

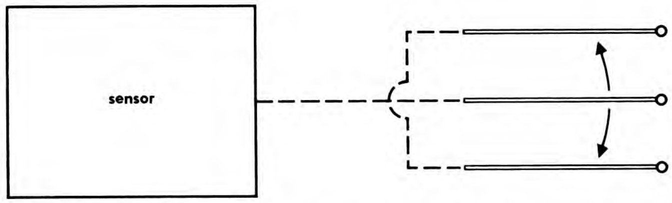

Figure 5E5.—Capacitance pickoff.

A movable plate is centered between the two fixed plates and connected to the sensor. The capacity between the center plate and the two outside plates is equal when there is no output from the sensor. If, however, a signal from the sensor causes the center plate to move toward the bottom plate, the capacity between these two plates will increase and the capacity between the top plate and the center plate will decrease.

This change in capacity can be used to vary the tuning of an oscillator. The change in oscillator frequency is then used for sense control. This type of pickoff is the most sensitive of all, since a very slight change in plate spacing will cause a large change in frequency.

F. Computing Devices

5F1. General

Computers appear in missile systems in a variety of forms. The computer may be a simple mixing circuit in a missile, or it may be a large console type unit suitable for use at ground installations only.

5F2. Function and requirements

One important function of a computer is the coding and decoding of information relating to the missile trajectory. It is necessary to code and decode control information in order to offset enemy countermeasures and to permit control of more than one missile at the same time.

Another function of the computer is the mixing of signals from sensor and reference units to produce error signals. Figure 5C1 shows, in block form, how the computer is linked with other sections of the complete system. The signals from the sensor and reference units may be mixed in a preset ratio, or they may be mixed according to programmed instructions.

The error signals produced by mixing are amplified and passed to the control actuating system and the followup section. The output of the followup section is then fed back to the computer for reprocessing. The purpose of feedback is to reduce overcontrol that would cause the missile to oscillate about the desired attitude.

The computer section may also compare two or more voltages to produce error signals. For this purpose, voltage or phase comparator circuits are added. The synchro units discussed in the previous section are used in computers to convert signal voltages into forms that are better suited for processing.

Airborne computers are generally classified according to the phase of missile flight in which they are used. The computers may be separate units or they may be combinations of prelaunch computer, launch computer, azimuth computer, elevation computer, program computer, and dive-angle computer.

5F3. Types of computers

In a missile control system, computer elements are of general types—mixers, integrators, and rate components.

MIXERS. As you will recall from the first part of this chapter, a mixer is basically a circuit or device that combines information from two or more sources. In order to function correctly, the mixer must combine the signals that are fed to it in the proper PROPORTION, SENSE, and AMPLITUDE.

The type of mixer used will depend mostly on the type of control system. Most systems use electronic mixers. However, mixers may also use mechanical, pneumatic, or hydraulic principles.

Electronic mixers may use a vacuum tube as a mixing device. Probably the most common type of tube mixer is the one used in conventional superheterodyne radio sets. Here a tube mixes an incoming RF signal with the signal of a local oscillator to produce a difference frequency. It is also possible to use a network composed of inductors, capacitors, and resistors for mixing. Regardless of the type of mixer, the signals to be combined are represented by the amplitude and phase of the input voltages. Voltages from such sources as pickoffs, rate components, integrators, followup generators, and guidance sources may be combined by the mixer section to form control signals.

Mechanical mixers consisting of shafts, levers, and gears can also be used to combine information. Figure 5F1 shows how lateral signals from two sources can be combined by using plain levers. To see how this works, assume that shafts 1 and 2 operate independently, and that their positions represent information that must be combined. The three connections pivot freely. The position of shaft 3 represents a weighted average of the other two shafts, because the vertical lever arms from shaft 3 are not of the same length. The direction of shaft movement gives sense information. The output of shaft 3 may be used to operate an electrical pick-off, such as a potentiometer.

Another mechanical mixer uses gears to combine position or angular velocity information. The gear arrangement is similar to that of an automobile rear axle differential. If the input shafts contain position information, they will move slowly and maintain approximately the same average position. The position of the output shaft constantly indicates the difference between the two shaft positions. If the information is represented by the speed of the shaft rotation, the angular velocity of the output shaft represents the difference between the two input shaft speeds.

It is possible to arrange the input shafts so that the output represents the sum of the inputs rather than the difference. Weighting factors can be controlled by changing the gear ratios in the differential.

Sometimes information is transferred through air or hydraulic tubes. The signals are created by varying the pressure inside the tube. Two signals can be combined by joining two tubes into one.

INTEGRATORS. An integrator performs a mathematical operation on an input signal. The

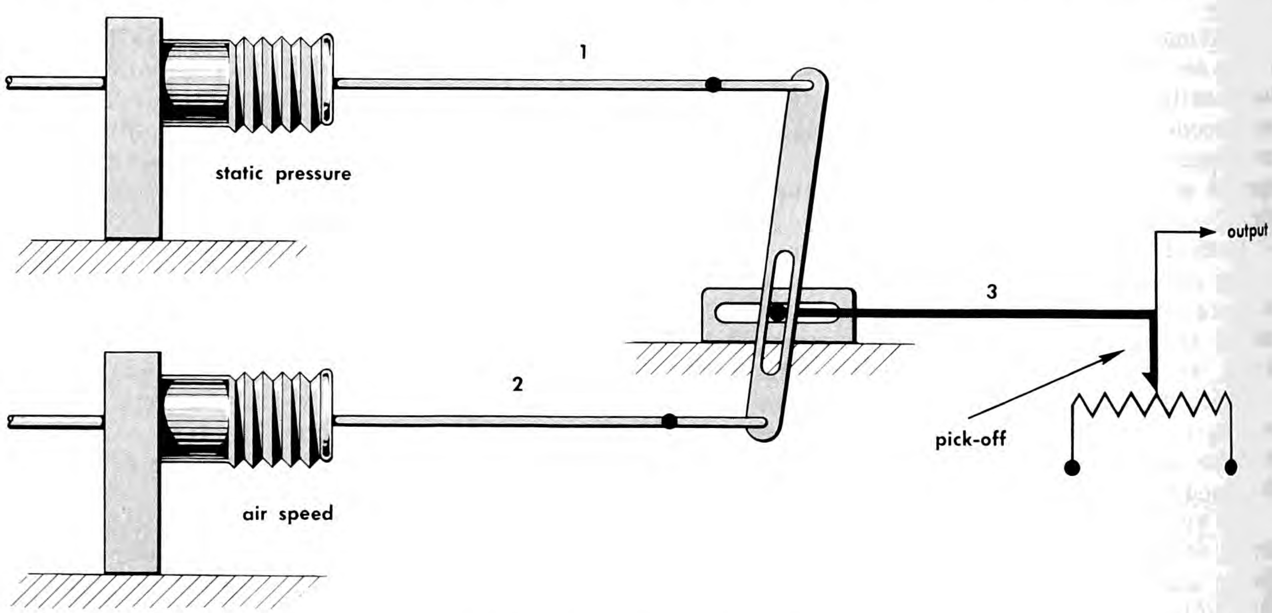

Figure 5F1.—Mechanical mixer.

integral of a constant signal is proportional to the amplitude multiplied by the time the signal is present. Assume that the integrator output is four volts when the duration of the constant input signal is one minute. Then if the same input signal had lasted for one-half minute, the output would have been two volts.

But, an actual missile error signal is not constant, as we assumed in the above example. The amplitude and sense of the error change continuously. Even so, the integrator output is proportional to the product of the operating time and the average error during that time. Should the sense of the error change during the integration period, a signal of opposite sense would cause the final output of the integrator to decrease. The integrator can be considered as a continuous computer, since it is always producing a voltage that is proportional to the product of the average input voltage and time. Therefore, the integration of an error with respect to time represents an accumulation of intervals of time and errors over a specified period.

Any integrator has a lag effect. To see why this is true, let us visualize a situation like that shown graphically in figure 5F2. The solid lines forming the rectangles represent on-off signals plotted with respect to time. The polarity is represented by the position of the rectangle above or below the time reference line. The heavy white lines represent the integrated output signal.

Although the input signal goes from zero to maximum with zero time lag, there is no output at that instant. The graph shows the lag effect; note that time is required before the output reaches an appreciable amplitude. Approximately the same length of time is required for the output amplitude to drop to zero after the input pulse ends.

The figure also shows the additive effect of two successive negative pulses. This action is made possible by the time lag, and is used to give more precise control action.

The output signal from the integrator is used to support the proportional error signal, to make sure that enough correction will always be made by the control system.

Keep in mind that the degree of control exerted by a pure proportional (unamplified) signal is limited. Over-control, or undercontrol, cause excessive movement of the missile about the desired trajectory. There are times when proportional control alone is not enough to overcome a strong, steady force that is causing the missile to deviate from the correct path. In a case of this kind, the proportional error signal will have a steady component that affects the integrator. The error signal sense remains constant, so that the integrator output increases with time as shown at the right of figure 5F2. This output increase reinforces the proportional signal until correction of the flight path takes place.

Integration may be performed by a motor, the speed of which is proportional to the amplitude of the input signal. The motor drives a pickoff, and the distance the pickoff moves is proportional to the integral of the input signal.

The direction of motor rotation will depend on the polarity or phase of the input signal. The amplitude of the error signal varies irregularly; the sense of the signal may reverse, causing reversal of the motor rotation.

Other types of integrators use ball-and-disk mechanical arrangement, resistance-capacity (R-C) circuits, resistance-inductance (R-L) circuits, and thermal devices.

RATE SYSTEMS. The rate section in a missile control system should produce an output signal proportional to the RATE OF CHANGE of the input signal amplitude.

The preceding section showed that a time lag is present in integrator circuits. It is this time lag that makes rate circuits necessary. Missile deviation cannot be corrected instantly, because the control system must first detect an error before it can begin to operate.

The ideal control system would have zero time lag, thus permitting zero deviation during the missile flight. All design efforts are toward a control system with this degree of perfection. Control surfaces are designed to correct missile flight deviations rapidly. The control surfaces are moved rapidly by actuators, which are operated by amplified error signals. But it is possible to have a signal so large that the missile is driven beyond the desired attitude, and an error occurs in the opposite direction. This error drives the missile back in the first direction. The end result is a series of swings back and forth across the desired trajectory.

These unwanted swings are known as oscillation (or hunting) and the addition of a rate signal has the effect of damping (retarding)

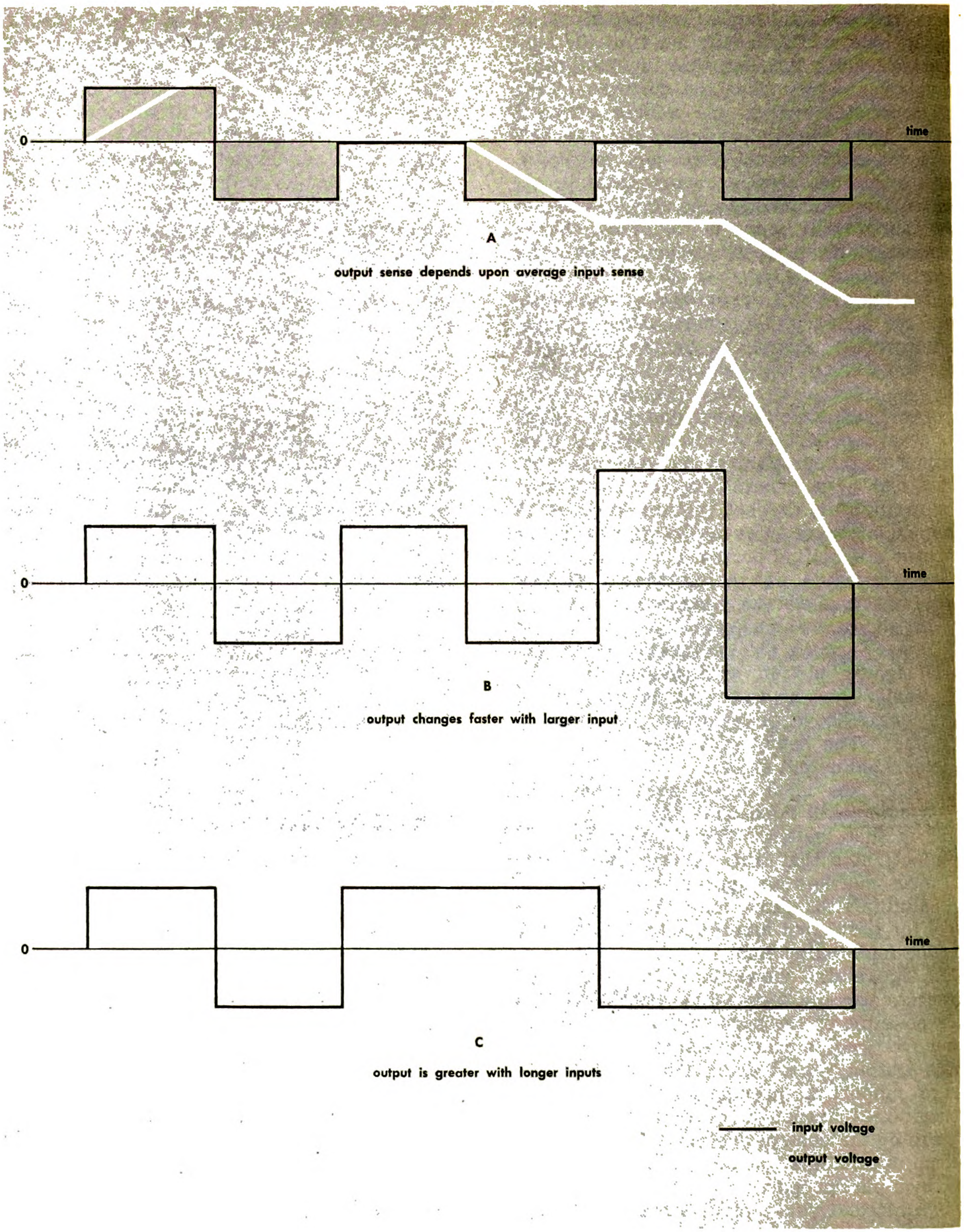

Figure 5F2.—Integrator time lag and sense.

the oscillation. The amount of damping may be classed as CRITICAL, UNDERDAMPING, or OVERDAMPING.

The end effect of a rate signal is a reduction in the time between the initial control pulse and the output action. To reduce this time, the rate signal is combined with the proportional signal to produce a resultant signal that leads the original proportional signal.

However, there is output from the rate device only when the missile deviation is changing. The amount of output is dependent on the rate of change. By combining the rate signal and the error signal, the system can be made to respond to a constant error. It is also possible to combine an attitude rate signal with a guidance signal.

Perhaps the most common method of producing a rate signal is by using a separate sensor unit, such as a rate gyro. As explained previously, the rate gyro construction is such that it can precess only a few degrees and in only one plane. Precession is restrained by a spring that tends to return the gyro to the midpoint. Any precession in this plane is caused by a force acting on the gyro gimbals. Such a force would be developed by any angular movement of the missile frame. The magnitude of the force would be proportional to the rate of movement. The gyro displacement is detected by a pickoff, and the output of the pickoff is the rate signal.

G. Amplifiers

5G1. Purpose

Amplifiers are divided into two groups—POWER and VOLTAGE. Both are used in missile control systems to build up a weak signal from a sensor so that it can be used to operate other sections of the control system. These sections normally require considerably more power or voltage than is available from the sensor. Most amplifiers use electronic tubes, but in this section we will discuss some of the less conventional amplifiers.

5G2. Operating principles

Some functions in missile control systems require a series of flat-topped pulses, called square waves, at a definite frequency. It is possible to convert other wave shapes to square waves with vacuum tube amplifiers and clippers. It is also possible to accomplish the same result with a mechanical device known as a chopper.

The chopper is a mechanical switch designed to operate a fixed number of times per second. A cutaway view of a mechanical chopper is shown in figure 5G1. This unit has the contacts arranged for single-pole double-throw switching, center OFF position.

The coil is excited by an a-c voltage that causes the vibrating arm to move at the frequency of the exciting voltage. Normally, the reed would vibrate at twice the a-c frequency—once each half-cycle. This can be prevented by incorporating a permanent magnet in the structure. Then, on one half of the a-c cycle the a-c field about the coil is reinforced by the permanent magnet field, and on the other part of the a-c cycle the field about the coil is opposed by the permanent magnet field. As a further aid to operation on the desired frequency, the vibrating reed is tuned for that frequency by weighting.

The contact arrangement is shown near the bottom of the drawing. Leads are brought out separately from each of the two fixed contacts and the vibrating reed to pins on the base. These pins are arranged so that the chopper can be plugged into a conventional radio tube socket. In order to reduce operating noise, the entire mechanism is enclosed in a sponge rubber cushion before it is placed in the metal can. By using the chopper in connection with a conventional transformer, amplification can be obtained at the pulse frequency.

Vacuum tubes can be used as electronic choppers. Other amplifiers, known as saturable reactors, are used for a-c motor control. This type of amplifier may sometimes be used in combination with vacuum tubes.

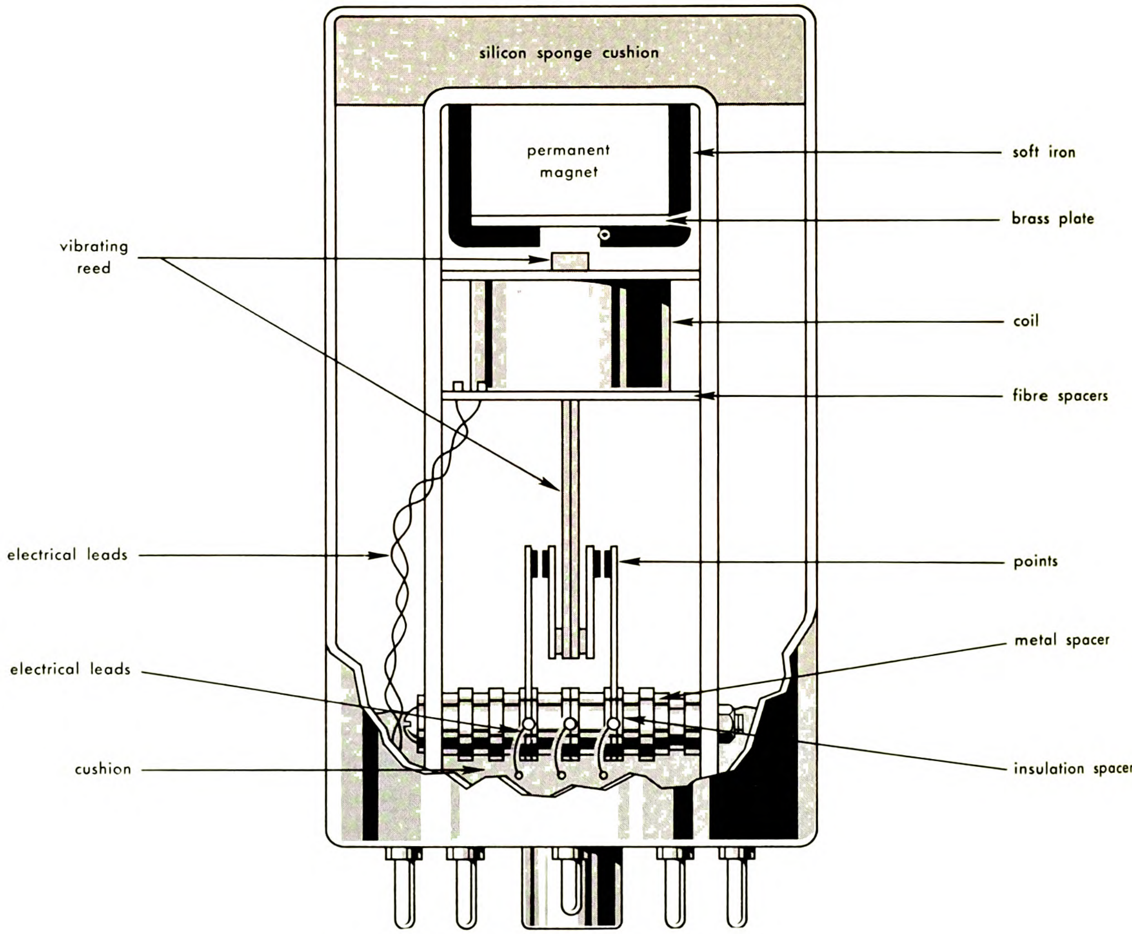

Figure 5G1.—Cutaway view of mechanical chopper.

H. Controller Units

5H1. Function

A controller unit in a missile control system responds to an error signal from a sensor. In certain systems an amplifier which is furnishing power to a motor serves as a controller. In this section we will discuss controller units other than amplifiers.

5H2. Types

There are several types of controllers and each type has some feature that makes it better suited for use in a particular missile system than other types.

SOLENOIDS. A solenoid consists of a coil of wire wound around a nonmagnetic hollow tube; a movable soft-iron core is placed in the tube. When a magnetic field is created around the coil by current flow through the winding, the core will center itself in the coil. This makes the solenoid useful in remote control applications, since the core can be mechanically connected to valve mechanisms, switch arms, and other regulating devices. Two solenoids can be arranged to give double action in certain applications.

TRANSFER VALVES. Figure 5H1 shows an application in which two solenoids are used to operate a hydraulic transfer valve. When

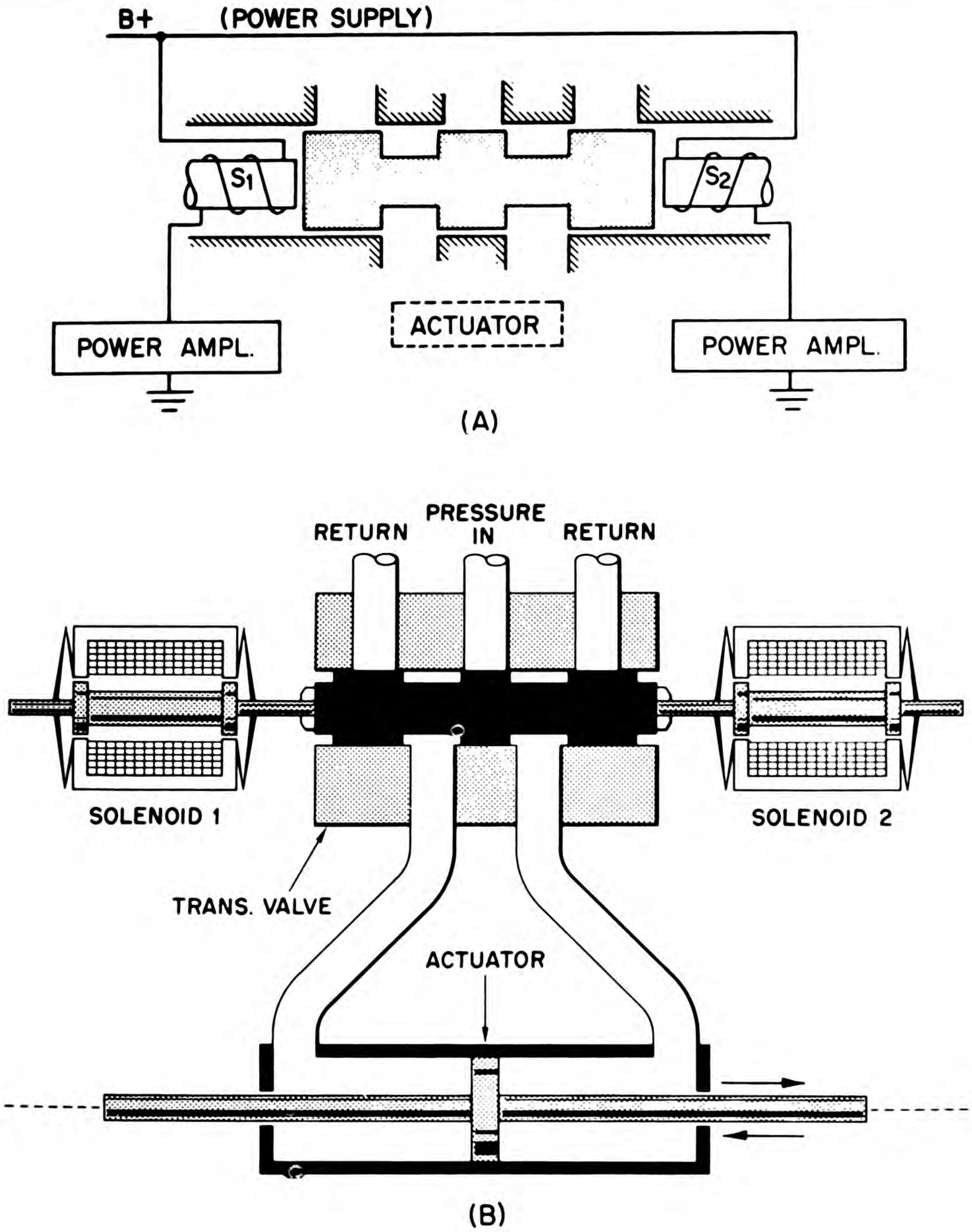

Figure 5H1.—a. Transfer valve (closed). b. Hydraulic transfer valve and actuator.

neither coil is energized, the valve is closed (fig. 5H1a). If S2 receives more energy, the center part of the valve section is pulled to the right, and the actuator is caused to move. The converse is true if more current flows thru S1. The actuator can be used to physically position a control surface.

RELAYS. Relays are used for remote control of heavy-current circuits. The relay coil may be designed to operate on very small signal values, such as the output of a sensor. The relay contacts can be designed to carry heavy currents.

Figure 5H2 shows a relay designed for controlling heavy load currents. When the coil is energized, the armature is pulled down against the core. This action pulls the moving contact against the stationary contact, and closes the high current circuit. The relay contacts will stay closed as long as the

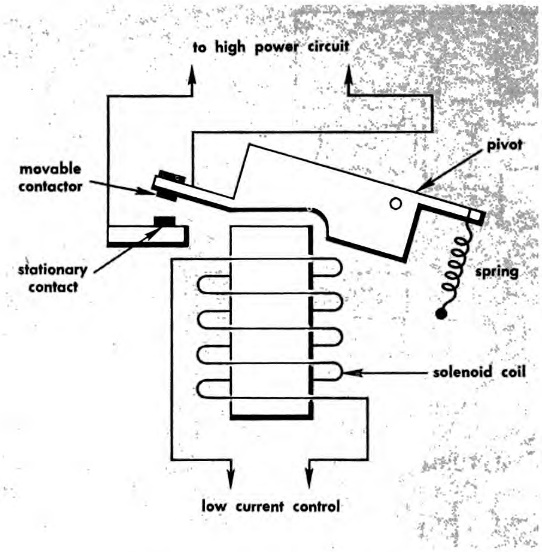

Figure 5H2.–Low current relay.

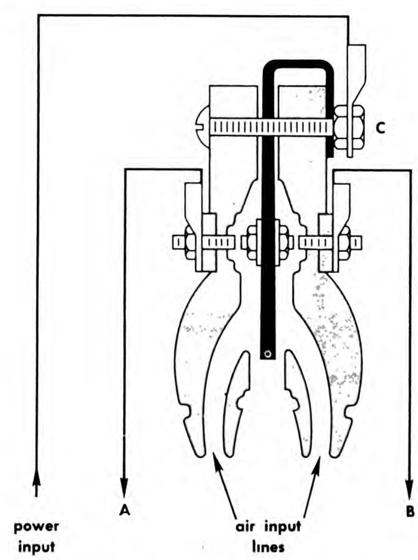

Figure 5H3.–Air-actuated relay.

magnetic pull of the coil is strong enough to overcome the pull of the spring.

The relay just described has a fixed core. However, some relays resemble a solenoid in that part of the core is a movable plunger. The moving contacts are attached to the plunger, but are electrically insulated from it.

Figure 5H3 shows a form of relay that can be used in a penumatic control system. Two air pressure lines are connected to the air input ports. The relay operates when its arm is displaced by air pressure. A modified design of this type relay might be used in a hydraulic-electric system in which case the diaphragm would be moved by hydraulic fluid pressure.

AMPLIDYNE. An amplidyne can be used as a combined amplifier and controller, since a small amount of power applied to its input terminals controls many times that amount of power at the output. Figure 5H4 shows an amplidyne.

The generator is driven continuously, at a constant speed, by the amplidyne drive motor. The generator has two control field windings that may be separately excited from an external source. When neither field winding is excited, there is no output from the generator, even though it is running. It follows that no voltage is then applied to the armature of the load driving motor. (The field winding of the motor is constantly excited by a d-c voltage.)

The control field windings of the generator are arranged so that the polarity of the excitation voltage from the sensor will determine the polarity of the generator output voltage. The generator output is connected to the load driving motor armature through the latter's commutator. Since the field of the motor is constantly excited by a fixed polarity, the polarity of the voltage applied to the armature will determine the direction of armature rotation.

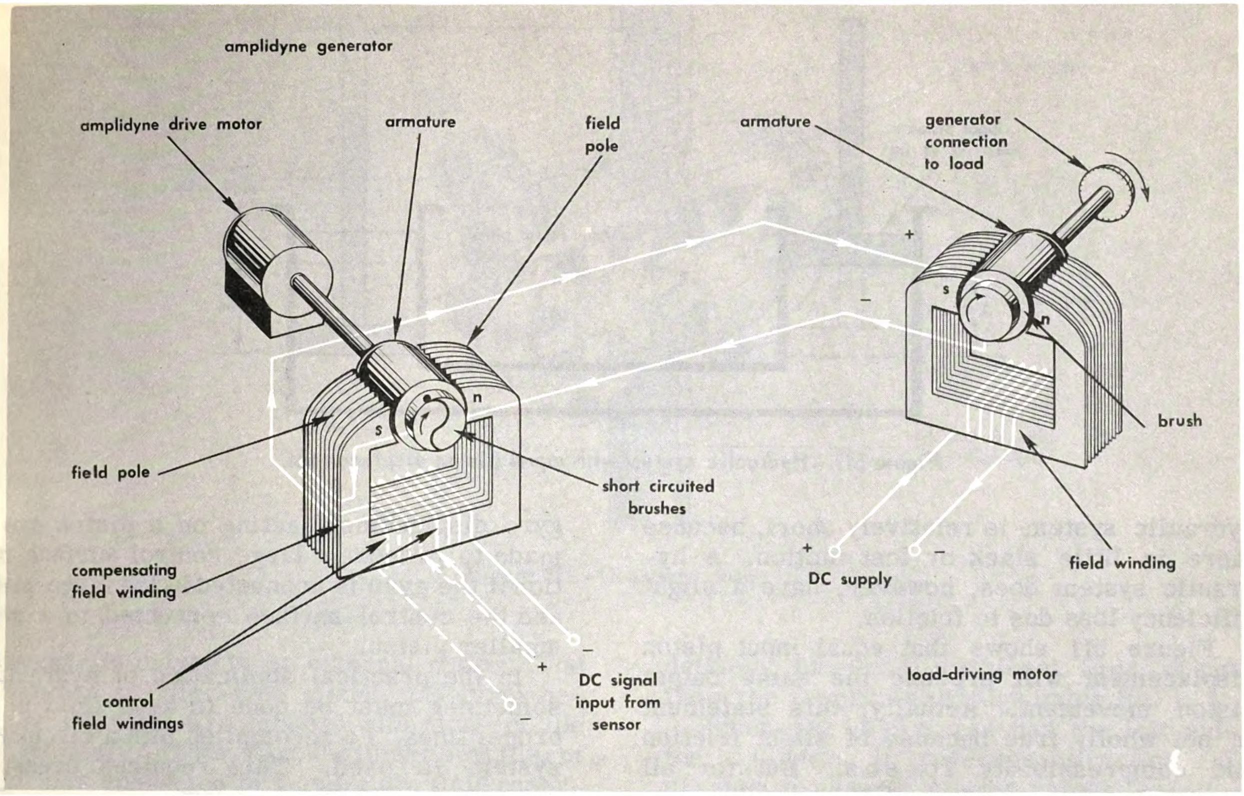

Figure 5H4.—Amplidyne controller.

I. Actuator Units

511. Function

In a missile control system, any error detected by a sensor must be converted into mechanical motion to operate the appropriate control device. The device that accomplishes this energy transformation is the actuator unit.

The actuator for a specific control system must be selected according to the characteristics of the system. The actuator must have a rapid response characteristic, with a minimum time lag between detection of the error and movement of the flight control surfaces. At the same time, the actuator must produce an output proportional to the error signal, and powerful enough to handle the load.

512. Principal types

Actuating units use one or more of three energy transfer methods: hydraulic, pneumatic, or electrical. Each of these has certain advantages, as well as certain design problems. We will discuss each system briefly.

513. Hydraulic actuators

Pascal's Law states that whenever a pressure is applied to a confined liquid, that pressure is transferred undiminished in all directions throughout the liquid, regardless of the shape of the confining system.

This principle has been used for years in such familiar applications as hydraulic door stops, hydraulic lifts at automobile service stations, hydraulic brakes, and automatic transmissions.

Generally, hydraulic transfer units are quite simple in design and construction. One advantage of a hydraulic system is that it eliminates complex gear, lever, and pulley arrangements. Also, the reaction time of a

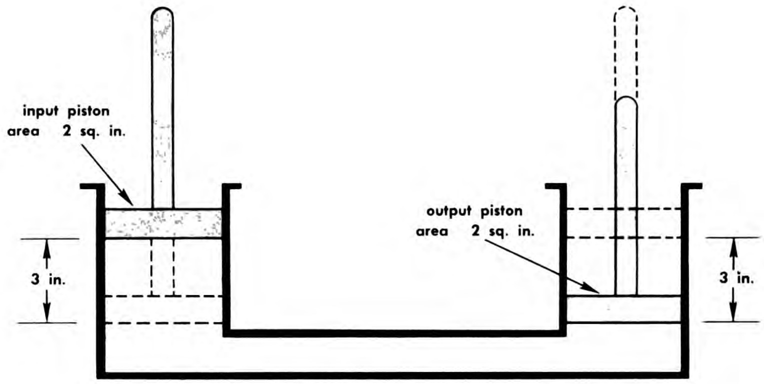

Figure 5I1.—Hydraulic system with equal piston displacement.

hydraulic system is relatively short, because there is little slack or lost motion. A hydraulic system does, however, have a slight efficiency loss due to friction.

Figure 5I1 shows that equal input piston displacement will produce the same output piston movement. Actually, this statement is not wholly true because of slight friction and compressibility losses. But for all practical purposes, the motion can be considered to be the same for equal piston displacements.

A different condition is shown in figure 5I2, where the output piston force has been increased. Because we can't get something for nothing, increased force results in a decrease in piston travel. Keep in mind also, that the output piston could be used as the input piston, and vice versa. Hypothetically then, a small gyro displacement acting on a piston can b made to produce a large control surface mo tion if the gyro is connected to the large pisto and the control surface connected to a muc smaller piston.

In the practical application of hydraulics something must be done to keep fluid in th proper lines. To accomplish this a circulatin system is used. This requires pressure which is furnished by a pump.

PUMPS. The pump used in a hydrauli system must be driven by some power source usually an electric motor, within the missile Pumps used in missile systems generally fal into two categories—gear and piston.

A gear type pump is shown in figure 5I3 It consists of two tightly meshed gears en closed in a housing. The clearance betwee the gear teeth and the housing is very small

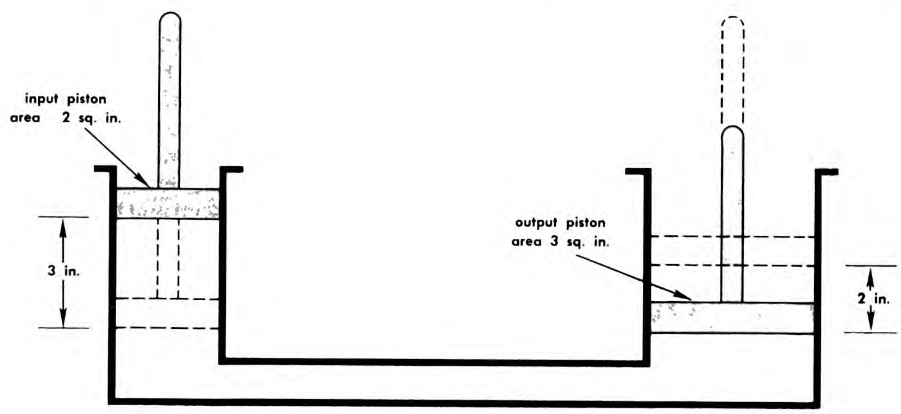

Figure 5I2.—Proportional hydraulic piston displacement.

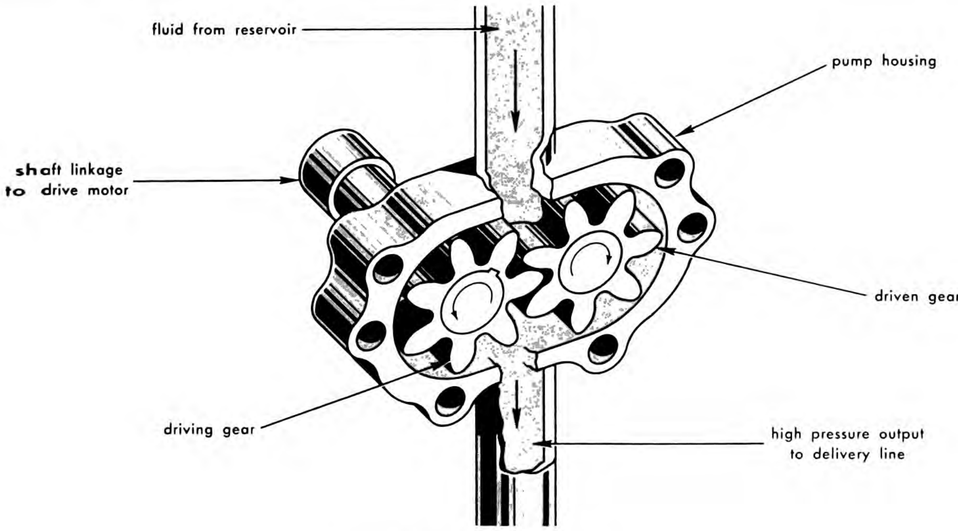

Figure 513.—Gear type pump.

One gear is driven by an external motor. The other has an idler-type mount, and turns because its teeth are meshed with those of the driven gear. In operation, the intake port (top of figure) is connected to a hydraulic fluid reservoir, and the output port is connected to the high-pressure delivery line.

As the gears turn past the intake port, fluid is trapped between the gear teeth and the housing. This trapped fluid is carried around the housing to the output port. Because the fluid then has no place else to go, it is forced into the high-pressure delivery line.

A double-action piston pump is shown in figure 514. This arrangement is called double action because fluid is pumped from the reservoir as the piston moves in either direction. To see how this happens, assume that the piston is at the extreme right of the cylinder, and that it has started to move to the left. A slight vacuum will be created as the piston moves, and this will reduce the pressure on valve No. 1. At the same time, system pressure will force valve No. 4 shut. Atmospheric pressure, which is admitted to the reservoir through regular inlets, will then act on the fluid which opens valve No. 1. At the same time, fluid to the left of the piston is being compressed. This forces valve No. 2 to close and block the path to the reservoir. The pump pressure forces valve No. 3 to open and, as a result, the fluid on the left side of the piston is forced into the delivery tube and additional fluid is pulled from the reservoir through valve No. 1.

When the piston reaches the left side of the cylinder, it reverses direction. This creates pressure against valves Nos. 1 and 4 so that valve 1 closes and valve 4 opens. At the same time, valve 3 closes and valve 2 opens.

RESERVOIR. The reservoir shown in figure 514 is a storage compartment for hydraulic fluid. Fluid is removed from the reservoir by the pump, and forced through the hydraulic system under pump pressure. After the fluid has done its work, it is returned to the reservoir to be used again. The reservoir is actually an open tank because of the atmospheric pressure inlets.

VALVES. The valves in the illustrated piston pump are of the flap type, which operate with very small changes in pressure. Another type of valve used in hydraulic systems is the pressure relief valve. As its name implies, it is used to prevent damage to the system by high pressures. Some combination systems use hydraulic pressure regulating switches instead of pressure relief valves.

A typical hydraulic relief valve is shown in figure 515. It consists of a metal housing with two ports. One port is connected to the hydraulic pressure line and the other to the reservoir return line. The valve consists of a metal ball seated in a restricted section of

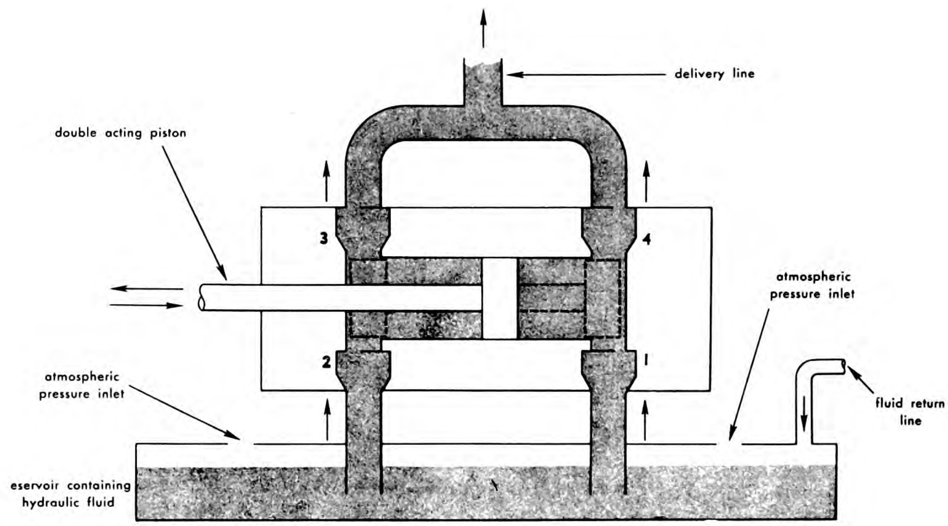

Figure 5I4.—Double-action piston pump.

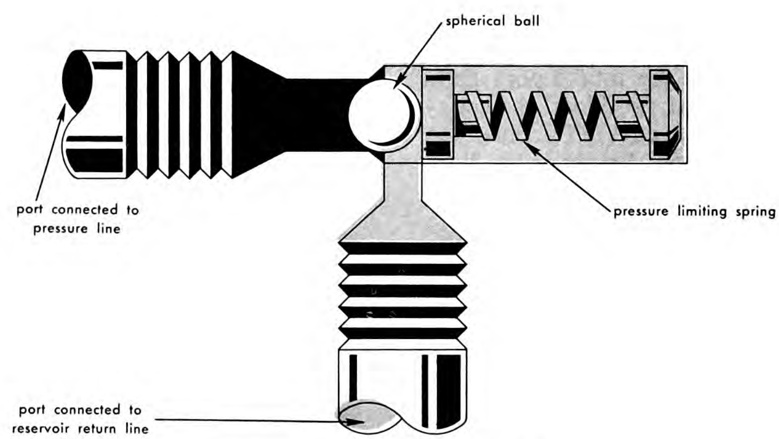

Figure 5I5.—Pressure relief valve.

the pressure line. The ball is held in place by a spring, the tension of which is adjusted to the desired lifting pressure. This pressure is chosen so that it will be within the safe operating limits of the system.

Should the system pressure become greater than the spring pressure, the ball will be forced away from the opening, and fluid will flow into the port that leads to the reservoir return line. Thus the pressure can never exceed a safe limit; and, since the fluid is returned to the reservoir, no fluid is lost.

ACCUMULATOR. We have shown that hydraulic fluid is stored in a reservoir under open tank conditions. When it becomes necessary to store hydraulic fluid under pressure,

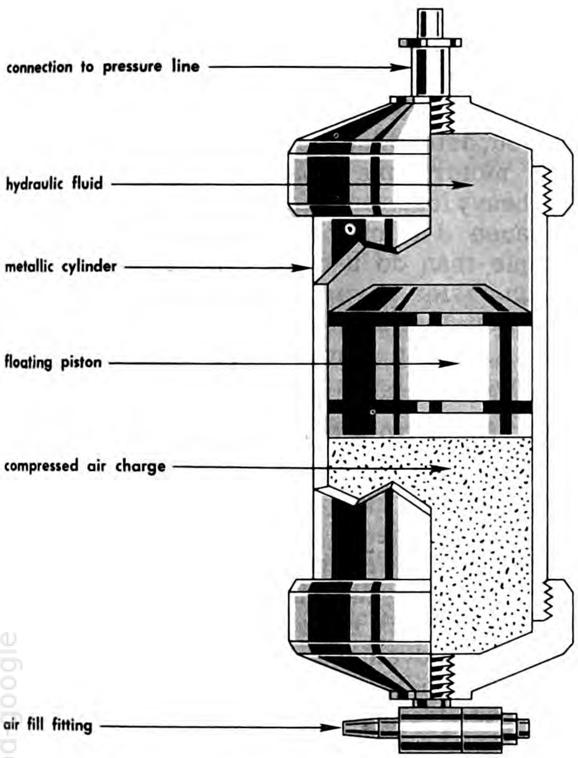

Figure 516.–Floating-piston hydraulic accumulator.

a storage space called a hydraulic accumulator is used. The accumulator also serves to smooth out the pressure surges from a double-action pump, which would otherwise cause unsteady operation of control devices to which the actuators are connected.

Figure 516 shows a floating-piston hydraulic accumulator. It consists of a closed metal cylinder separated into two compartments by a floating piston. One compartment is an air chamber and the other a fluid chamber.

In operation, the air chamber is charged, through the bottom fitting, with compressed air until the chamber pressure equals the line pressure desired in the hydraulic system. This pressure forces the piston up toward the top of the cylinder. The cylinder is connected to the hydraulic pressure line through the fitting at the top. If the line pressure becomes greater than the air pressure, fluid is forced into the accumulator, and forces the piston down against the air pressure. Should line pressure drop, the air pressure forces the piston up and puts fluid back in the line. This action smooths out variations in pressure during periods of heavy loading, or when the pressure pump lags.

Another type of hydraulic accumulator, the diaphragm type, is shown in figure 517. It is built in the form of two hemispherical chambers, which are separated by a flexible diaphragm. Air pressure forces the diaphragm upward. If the system pressure becomes greater than the air pressure, fluid is forced into the fluid chamber. When the system pressure drops, air pressure in the accumulator forces the working fluid back into the system. The diaphragm-type accumulator serves the same purpose in a hydraulic control system as the piston type.

ACTUATOR. The purpose of a hydraulic actuator in a missile control system is to convert fluid pressure into mechanical force great enough to move a control device.

A basic actuator consists of a cylinder with fluid intake and exhaust ports, and a piston which is mechanically connected to the

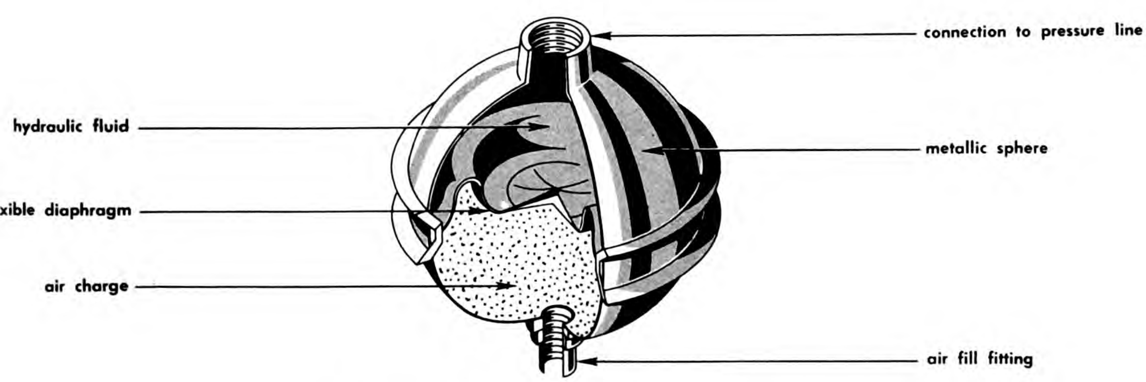

Figure 517.–Diaphragm-type accumulator.

load. It is possible to have a double-acting piston-type actuator in which hydraulic fluid under pressure can be applied to either side of the piston. A double-action actuator is shown in figure 5H1b.

5I4. Pneumatic

The principal difference between a hydraulic system and a pneumatic system is the use of air rather than hydraulic fluid, as the working medium.

In a pneumatic system, air from a pressure tank passes through delivery tubes, valves, and pressure regulators to operate mechanical units. After the air has done its work, it is exhausted to the atmosphere. It cannot be returned to the tank for reuse. Consequently, air must be stored at a much higher pressure than is necessary for operating the loads in order to have enough pressure to operate the controls as the air supply in the tank diminishes.

A pneumatic control system is shown in figure 5A8, and a brief explanation of the operating sequence is given in the accompanying text.

5I5. Electrical

Generally, motors are used as actuators in electrical control system. The size of the load, and the speed with which it must be moved, determine the type of motor to be used. D-c motors are most often used for driving the heavy loads encountered in missile systems, because d-c motors develop a higher stall torque than do a-c motors. In addition, it is much easier to vary the speed of a d-c motor.

Electrical systems were described in section A, and an electrical pitch control system is shown in figure 5A12.

5I6. Mechanical linkage

We have discussed the various control systems, but have not discussed in detail the mechanical means of linking the flight control surfaces to the actuator. In addition to providing a coupling means, the linkage may also be used to amplify either the force applied or the speed of movement.

A mechanical linkage between an actuator and a load is shown in figure 5I8. The distance,

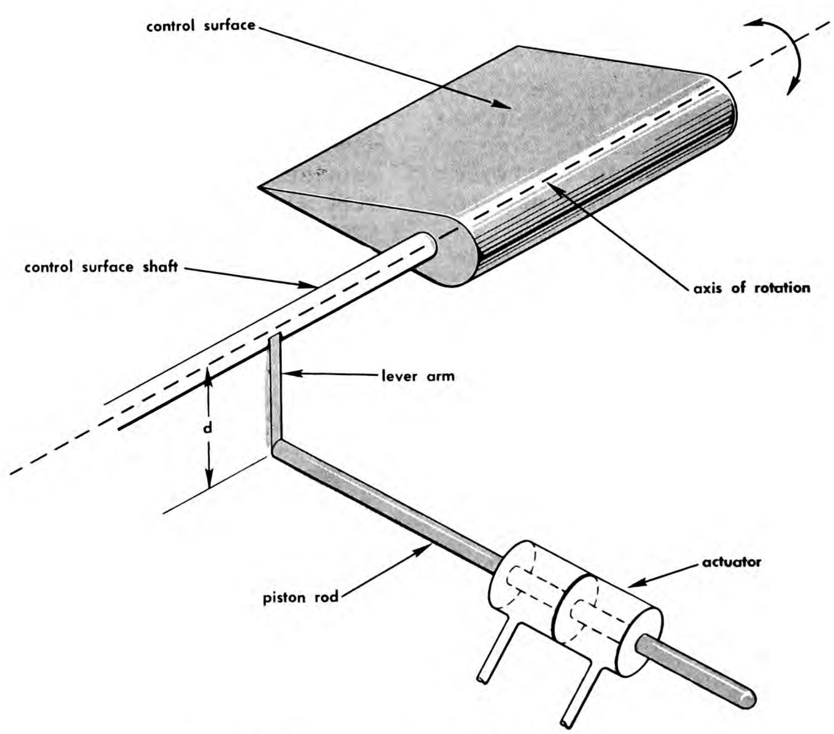

Figure 5I8.—Actuator and load linked by lever arm.

d, on the drawing represents the distance from the control surface shaft to the point where the force is applied. The control surface moves because force exerted by the piston is applied at a distance from the axis of rotation, and thus produces a torque. Other mechanical linkages may consist of an arrangement of gears, levers, or cables.

517. Combination systems

Often a number of mechanical systems will be grouped together to form a combination system, as shown in figure 5I9. This system uses levers, cables, pulleys, and a hydraulic actuator. However, a system using this kind of control is not suited for high speed missiles.

518. Followup units

The followup unit in a missile control system plays an important part in obtaining a smooth trajectory with minimum oscillation. It does this by providing continuous information on flight control surface position in relation to the missile axes. The followup signal indicates how the output section of the control system is following the correction data initiated by the sensor unit.

Without a signal of this type, the control surface would swing to their limit stops any time the actuator got a signal from the sensor. The followup signal makes possible a control surface deflection proportional to the magnitude of the error.

In operation, the followup signal combines with the error signal so as to oppose it. But, the error signal is the larger of the two, and is strong enough to produce the necessary control surface deflection. The error signal amplitude decreases as the missile approaches the correct flight path. When the amplitudes of the error and followup signals are equal, there is no further deflection of the flight control surfaces, because the sum of the two signals is zero.

An electrical followup system is shown in figure 5I10. In this system, the error signal is supplied to an electronic mixer where it is combined with the smaller signal from the followup generator. The difference, or resultant, of these signals is fed through an amplifier and controller to the actuator section that operates the control surface. A portion of this signal is also fed to the followup generator, so that the followup signal is proportional to the flight surface deviation from the axis line.

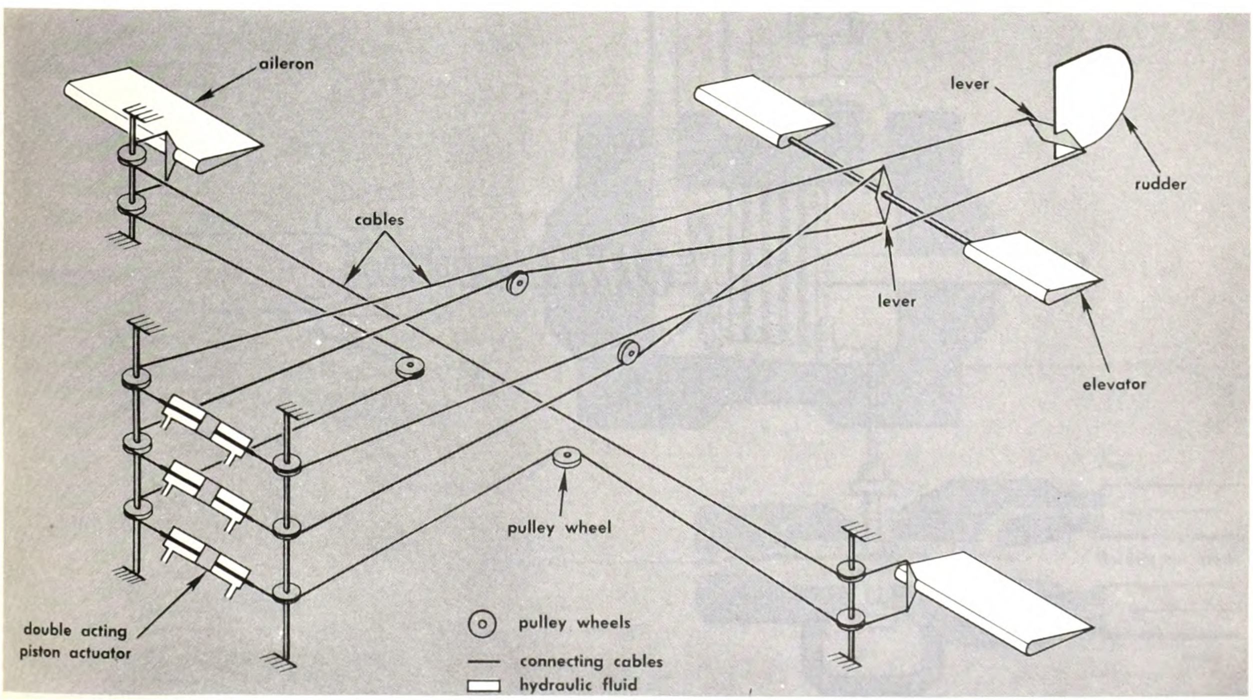

Figure 5I9.—Combination mechanical linkage.

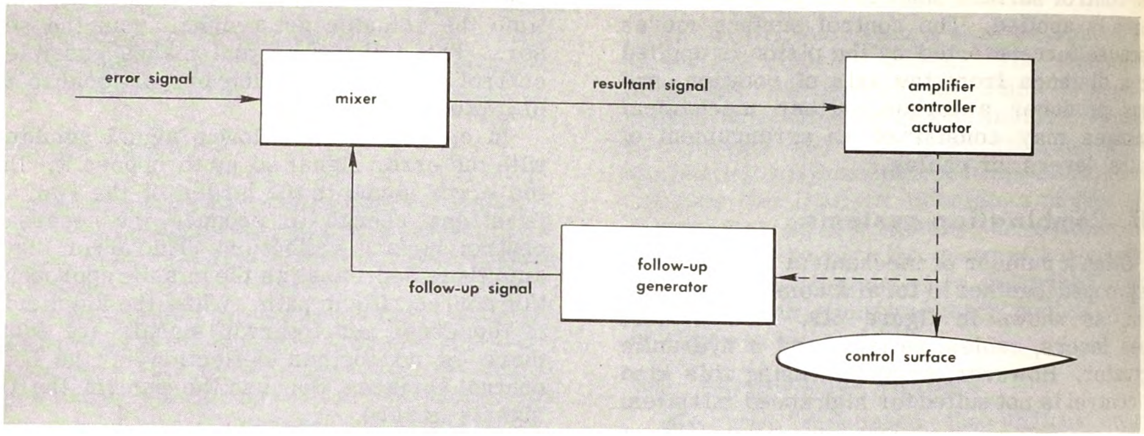

Figure 5I10.—Followup loop of missile control system.

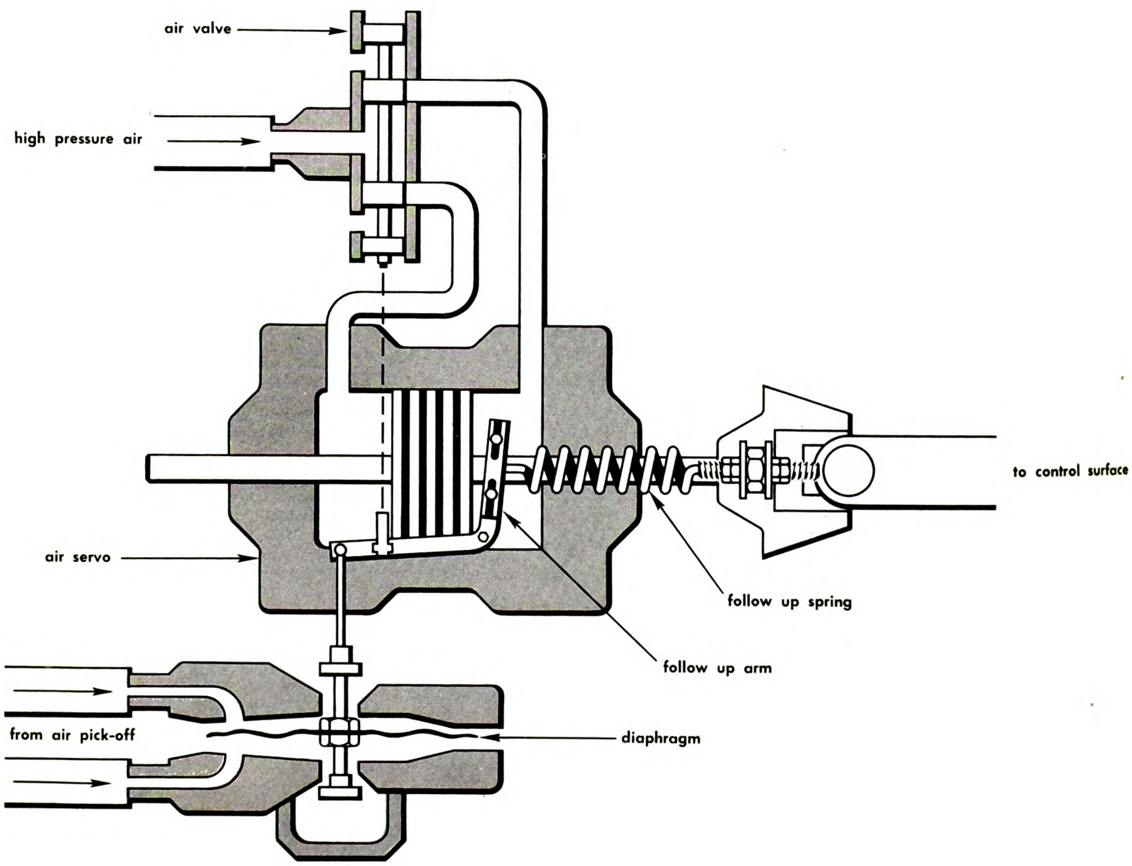

Figure 5I11.—Air relay with mechanical followup.

It is also possible to use a mechanical followup. When this method is used, the followup mechanism may be a part of an air relay as shown in figure 5I11. The control surface position in relation to the missile axis is indicated by a force which is reflected to the controller by a spring.

To see how this system operates, assume that the signal from a pneumatic pickoff moves the air relay diaphragm up. The followup arm will then move clockwise. This movement causes the valve spool of the air valve to move upward. The valve action admits high-pressure air to the relay, and the pressure forces the piston of the pneumatic actuator to the left. When this happens, the followup spring is compressed and tends to turn the followup arm in a counter-clockwise direction. Since the followup force is in opposition to the original motion of the followup arm, we have the desired inverse feedback.

A large signal will create a larger flight control surface deflection before the feedback force becomes great enough to return the followup arm to zero. The spring will then push the followup arm and the air valve in the opposite direction, to move the flight control surface back. Therefore, the spring acts to limit flight surface deflection to a value determined by the error signal, and to return the flight control surface to a position parallel with the missile axis.

CHAPTER 6

PRINCIPLES OF MISSILE GUIDANCE

A. Introduction

6A1. General

From an offensive viewpoint, a missile can be considered as a long-range artillery projectile. In its basic form, a missile is a self-propelled, high-explosive weapon. Like a projectile, it must be carefully aimed in order to follow a trajectory that will take it to the target.

Missiles like projectiles, are influenced by natural forces such as cross winds. But, because a missile usually makes a much longer flight than a projectile, it is subjected to these natural influences for a longer time.

A missile is a very expensive piece of ordnance. If the conventional artillery practice of firing several ranging shots were followed, the cost would be prohibitive. And unguided missiles would be of little value against moving targets, which can take evasive action.

All of these factors add up to this: an accurate means of guiding a missile to its target is an absolute necessity.

Modern guidance systems are far advanced. But progress in electronic and allied equipments is rapid, and our present guidance systems may be out of date within a few years. The ultimate system may be a composite formed from the systems you will read about in this and the following chapters, or it may be entirely different from any of them.

6A2. Definitions

A GUIDED MISSILE may be defined as an unmanned projectile that carries its own flight control equipment. In addition, the missile carries a payload—either of explosives or of scientific equipment. High-altitude missiles are used to obtain data on conditions existing far above the earth. Missiles equipped with guidance control and scientific instruments have been shot into the "mushroom cloud" that forms after an atomic blast, to obtain data on radioactivity, temperatures, and other effects. Since missiles have a number of peacetime applications, they should not be considered exclusively as weapons.

The word GUIDED means that the missile flight surfaces are operated by a control system within the missile, in much the same way as if a human pilot were aboard the missile guiding it to the desired target.

6A3. Purpose and function

The purpose of a guidance system is to control the path of the missile while it is in flight. This makes it possible for personnel at ground or mobile launching sites to hit a desired target, regardless of whether that target is fixed or moving, and regardless of whether or not it takes deliberate evasive action. The guidance function may be based on information provided by sources inside the missile, or on information sent from fixed or mobile control points, or both.

6A4. Basic principles

The guidance system in a missile can be compared to the human pilot of an airplane. One guidance system uses an optical device that guides the missile to the target in much the same way as a pilot, using landmarks for bearings, guides a plane to a landing field.

If landmarks are obscured, the pilot must use another system of guidance. He could, for example, use radio beams. One missile guidance system uses radio or radar beams for guidance; another uses radio to send information to the missile, just as a ground control station might send instructions to a pilot.

We have mentioned radio and radar as primary guidance controls, but these are not the only methods by which a missile trajectory can be controlled. Heat, light, television, the earth's magnetic field, and loran have all been found suitable for specific guidance purposes. Information on all these systems will be given in later chapters.

When an electromagnetic source, such as radio or radar, is used to guide the missile, an antenna and receiver are installed in the missile to form what is known as a SENSOR. The sensor section picks up, or senses, the guidance instructions. Missiles that are guided

by other means use different sensor elements. But the missile control sections, which follow the sensor section, are basically similar for all types of guidance.

B. Phases of Guidance

6B1. General

For purposes of explanation, missile guidance may be divided into three separate phases. The first is known as the LAUNCHING, or INITIAL phase. The second is called the MIDCOURSE phase, and the last is called the TERMINAL phase. These names refer to different parts of the missile flight path.

6B2. Initial phase

Missiles may be launched from a point at some distance from the guidance equipment. Because the missile does not have aerodynamic stability when it is first launched, the flight controls are locked in the neutral position, and remain locked for a short time after launching. As soon as the controls are unlocked, and the guidance system assumes control, the initial phase of guidance is completed.

6B3. Midcourse phase

The second, or midcourse phase of guidance is often the longest in both distance and time. During this part of the flight, changes may be required to bring the missile onto the desired course, and to make certain that it stays on that course. During this guidance phase, information can be supplied to the missile by any of several means. In most cases, the midcourse guidance system is used to place the missile near the target, where the system to be used in the final phase of guidance can take over. But, in some cases, the midcourse guidance system is used for both the second and third guidance phases.

6B4. Terminal phase

The terminal phase is of great importance because it can mean a hit or a miss. The last phase of surface-to-air missile guidance must have high accuracy as well as fast response to guidance signals.

Near the end of the flight, the missile may lack the power necessary to make the sharp turns that are required to overtake and score a hit on a fast-moving target. In order to decrease the possibility of misses, special systems are used. These systems will be described in the following chapters.

C. Components of Guidance Systems

6C1. General requirements

A missile guidance system involves a means of determining the position of the missile in relation to known points. The system may obtain the required information from the missile itself; it may use information transmitted from the launching station or other control point; or it may obtain information from the target itself. The guidance system must be stable, accurate, and reliable.

In order to achieve these basic requirements, the guidance system must contain components that will pick up guidance information from some source, convert the information into usable form, and activate a control sequence that will move the flight control surfaces on the missile.

Because it is difficult to separate the control and guidance operations, we will go through the entire guidance system. However, the flight control section is concerned with flight stability. Missile accuracy is primarily a function of the guidance section. Missile reliability depends on both sections. We will list the components and briefly describe the basic function of each before going into the individual types of guidance systems.

6C2. Sensor

In some respects, the sensor unit is the most important section of the guidance system because it detects the form of energy being used to guide the missile. If the sensor unit fails, there can be no guidance.

The kind of sensor that is used will be determined by such factors as maximum operating range, operating conditions, the kind of information needed, the accuracy required, viewing angle and weight and size of the sensor, and the type of target and its speed.

Acoustic sensors called hydrophones are often used in torpedo guidance systems. Essentially, a hydrophone is a microphone that works underwater. It picks up the vibrations of ships' propellers, and the torpedo can "home" on this noise. Acoustic sensors are not well suited for airborne missiles.

Heat, or infrared sensors use an active element called a THERMOCOUPLE, or an element known as a BOLOMETER. Either sensor may be used with a lens and reflector system.

Sensors that respond to light use an active element called a PHOTOELECTRIC cell. Another light-sensing system uses a television camera to pick up information and send it back to the launching site by means of a TV transmitter in the missile.

Electromagnetic sensors use radio or radar antennas as active elements. The phase of guidance determines the location of the antenna in the missile structure. For initial and midcourse guidance the antenna is normally streamlined into the tail of the missile. For final phase guidance the sensor may be located in the nose of the missile.

All of these sensors have advantages and disadvantages. Some are well suited for final phase applications and totally unsuited for initial and midcourse guidance. The advantages and disadvantages of each will be covered in later chapters.

6C3. Reference units

The signals picked up by the sensor must be compared with known physical references such as voltage, time, space, gravity, the earth's magnetic field, barometric pressure, and the position of the missile frame. The sensor signal and the reference signal are compared by a computer, which will generate an error signal if a course correction is necessary. The error signal then operates the missile control system.

Gyroscopes are used for space reference. A reference plan is established in space, and the gyro senses any change from that reference.

The earth's gravity can be used as a reference; a pendulum can sense the direction of the gravitational force. Some gyros are arranged for vertical reference by a pendulous pick-off and erection system. Gyros used in this manner are called vertical gyros; they may be used to control the pitch and roll of the missile.

An instrument called a FLUX VALVE, has the ability to sense the earth's magnetic field, and can be used for guidance. The primary purpose of this device is to keep a directional gyro on a given magnetic heading. A gyro operated in this manner may be used to govern the yaw controls of a missile.

Barometric pressure can be used to determine altitude. A guided missile that is set to travel at a predetermined altitude may use an altimeter to sense barometric pressure. Should the missile deviate from the desired altitude, an error signal will be generated and fed to the control section.

Another pressure-type sensor is used to determine airspeed. It compares static barometric air pressure with ram air pressure. The difference between these two pressures provides an air speed indication.

The axis of the missile frame is used as a reference to measure the displacement of the missile control surfaces. (The movement of the control surfaces cannot be referenced to the vertical, or to a given heading, because the reference would change when the missile position changes.)

Selsyns may be used to indicate the angular position of the flight control surfaces with respect to the missile axis. It is also possible to use potentiometers (variable resistors) for this purpose. When this method is used, the potentiometer is fastened to the missile frame and the potentiometer wiper-arm shaft is moved by the control surface.

6C4. Amplifiers

Each of the sensor units we have discussed produces an output; in most cases this output is a voltage. A computer is used to compare the sensor output voltage with the reference voltage. If the missile is off course, the two voltages will not be the same. The computer will then generate an error signal, which will be used to operate the missile control surfaces and bring the missile back on course.

But the computer output power is usually too small to do the actual work of moving the control surfaces. And the output of a sensor

unit is often too small for accurate comparison with a reference voltage. In such cases the missile uses an AMPLIFIER to increase either the signal voltage or power, or both, to a useful value. A transformer is a simple, familiar device that can increase an a-c voltage. The voltage across the secondary winding may be many times as high as the voltage applied to the primary. But the current available in the secondary circuit is proportionately smaller than that applied to the primary, so that there is no increase in power. There is no device that will give out more power than you put into it; in other words, you can't get something for nothing.

In an amplifier, the small power available in the input signal is used to CONTROL the amount of power that is supplied from another source. Thus, in a sense, a relay or a switch is an amplifying device. A small amount of power applied to the relay primary, or to the switch handle, will close the contacts and thus apply a much larger amount of power to the load. But a switch or relay is an all-or-nothing device; the contacts are either open or closed. Many missile applications require an amplifier whose output is not only greater than the input, but also proportional to the input. For example, let's say that a sensor provides a one-volt input to an amplifier, and the amplifier output is 15 volts. Then, if the sensor supplies a three-volt input, the amplifier output must be 45 volts.

Electronic amplifier circuits can be designed to give proportional amplification for a limited range of input voltages. Electronic amplifiers have become familiar devices. An electronic amplifier is used to amplify the output of a record-player pickup to the power level required to drive a loudspeaker cone. Electronic amplifiers are used to amplify the signals picked up by a radio antenna. (But note that, in both cases, the actual power of the input signal is not increased. The input power is used simply to control the power supplied from another source—either batteries or the a-c line.)

At present, most electronic amplifiers are based on vacuum tubes. As you probably know, a vacuum tube is a sealed envelope of glass or metal, from which most of the air has been exhausted. A vacuum tube used in an amplifier circuit contains a cathode, a plate, and one or more grids. The cathode, which is electrically heated, is connected to the negative side of the power supply. The plate, which is not heated, is connected to the positive side. Under these conditions, an electric current will flow from the cathode to the plate, through the vacuum in the tube. The control grid is usually a spiral of wire surrounding the cathode, and much closer to the cathode than it is to the plate. The voltage applied to the grid can be used to control the flow of current through the tube.

Let's consider a very simple application, in which a vacuum tube is used as a switch. Let's say that we want a relay to operate when light falls on a photoelectric cell (fig. 6C1). If we apply a voltage across a photoelectric cell, and the cell is dark, the current flowing through it will be close to zero. But the current will increase slightly when light falls on the cell. Because the current in the photo tube circuit is only a few millionths of an ampere, it is not sufficient to operate a relay. But if we connect a resistance in series with the photo cell, this current will develop a voltage across the resistance, in accordance with Ohm's law. By using a very large resistance in series with the photo tube we can develop several volts across it, even though the power is very small. This voltage can be applied to the grid of a vacuum tube. Then, when light falls through the photo cell, current will flow through the vacuum tube; when the cell is dark, no current will flow. In this way, the flow of current CONTROLLED by the photo cell may be several thousand times as much as the current that actually flows through it. Finally, we can connect the coil of a suitable relay in series with the vacuum tube, between

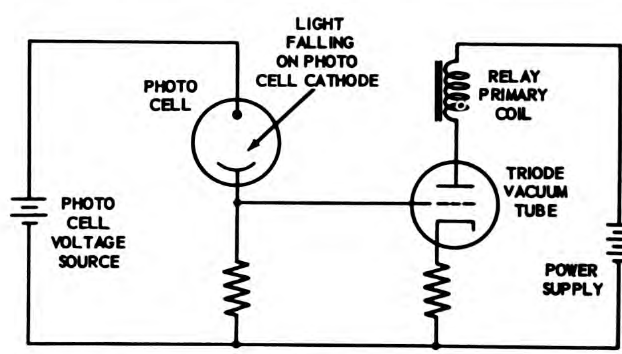

Figure 6C1.—Photoelectric cell with vacuum tube amplifier.

its plate and the positive terminal of the power supply. Then, when light falls on the photo cell, the relay contacts will close; when the light is removed from the cell, the relay contacts will open again.

A vacuum tube is more often used to amplify an a-c input signal (fig. 6C2). For this purpose, a plate load resistor is connected in series with the tube, between the plate and the positive terminal of the power supply. A changing current through the tube will then produce a corresponding change across the load resistor, in accordance with Ohm's law. In most circuits a steady, negative d-c voltage is applied to the grid. When no input signal is present, this negative "bias" voltage maintains the tube current at about half its maximum value. When an a-c input signal is applied to the grid, it will alternately add to and subtract from the fixed bias. The plate current, and consequently the plate voltage, will follow the input signal, but at a much increased amplitude. The output signal is taken

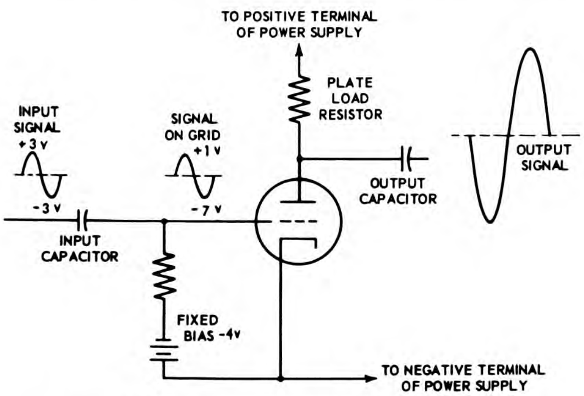

Figure 6C2.–Vacuum tube used as a-c amplifier.

from the plate, usually through a capacitor. This output can, of course, be used as the input for a second stage of amplification, so that extremely small signals can be built up to useful levels.

For many applications, transistors can be used in place of vacuum tubes. In a transistor, a current flows through a metallic semiconductor, rather than through a vacuum. The flow of current can be regulated by an input signal applied to a third terminal, so that the transistor can be used as an amplifying device. Transistors are less sensitive to vibration than vacuum tubes; they are considerably smaller, and they require no cathode heating power. On the other hand they are unreliable at high temperatures, and are not available on the market in as wide a variety of types. Finally, they are ineffective at the extremely high frequencies present in many vacuum tube circuits. In guided missile circuitry, transistors have begun to displace vacuum tubes in some applications.

Another amplifying device is the MAGNETIC AMPLIFIER. In its simplest form, this device is basically a transformer with a saturable core, and a third winding in addition to the usual primary and secondary (fig. 6C3). With no current in the third winding, the device acts like a transformer, and an a-c voltage is developed in the secondary circuit. By passing d-c through the third winding, the core can be saturated; there is then no transformer action, and the secondary develops no voltage. A varying input signal on the third winding produces a corresponding variation, of greater amplitude, across the output. Most of the magnetic amplifiers now in use are more sophisticated than the one described here; they have additional windings, and serve a variety of purposes.

A magnetic amplifier is a reliable device because it is rugged, and resistant to shock, vibration, and temperature changes. It is used in a number of missile applications.

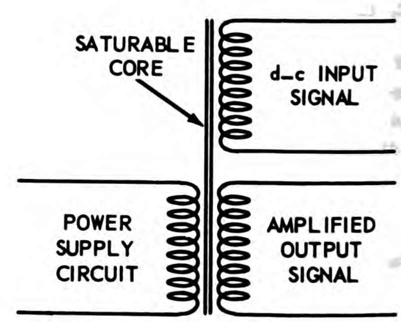

Figure 6C3.–Simplified diagram of magnetic amplifier.

6C5. Computer

A computer is necessary in missile guidance systems in order to calculate course corrections rapidly. In one type of missile the computer is simply a mixing circuit. On the

other hand, the computers used at launching sites may be large consoles with many stages.

An important function of a computer is the coding and decoding of information relating to the missile trajectory. In order to make the proper selections, the computer uses discriminator circuits to select pulses of the proper width, amplitude, frequency, phase, or time difference, and reject all other pulses. By using a number of different discriminators, a wide variety of pulse characteristics can be handled. The discriminator is relatively insensitive to manmade electrical noises and atmospheric static.

A second important computer function is to compare the signals from the sensor and reference units, to compute the missile's position with respect to the desired reference planes, and to generate error-signal voltages of the polarity and amplitude required to bring the missile back on course.

Computers may be divided, according to the way they operate, into two classes: ANALOG and DIGITAL. An analog computer deals with quantities that are continuously variable. A target bearing angle, for example, is such a quantity; in an analog computer, such a quantity can be represented with considerable accuracy by a voltage, or by the angle of rotation of a shaft. Digital computers, on the other hand, deal only with quantities that vary by distinct steps. For example, an angle might be represented as either 67° or 68°, but not as anything between those values. (A more complex computer might represent the same angle as either 67.43° or 67.44°, but would be incapable of dealing with any value between those two.) An ordinary slide rule is a simple analog computer, in which the position of the slide is "analogous" to the quantity represented. A desk calculating machine, or an abacus, is a simple digital computer.

Both analog and digital computers have applications in guided missiles and their associated ground equipment, although analog computers are more often used. Computers of either class may operate either electrically or mechanically, or by a combination of these two means. In a mechanical analog computer, the input and output variables are usually represented by angles of shaft rotation. The computer performs its various calculations through the movement of shafts, gear trains, slides, linkages, and other mechanical devices. Computers using these principles have been used to solve navigation and fire control problems for a number of years.

In an electronic analog computer, the input and output variables are represented by voltages, and the computations are performed by electronic circuits. A type of electronic analog computer that has proved useful in missile design is the DIFFERENTIAL ANALYZER. This device is sometimes called a SIMULATOR, because it can be given electrical inputs that simulate both the characteristics of a proposed missile and the conditions under which it will operate. The action of the computer will then show how the proposed missile will perform under the specified conditions. It is thus possible to test new missile designs without building actual prototype missiles, and this procedure results in a considerable saving in both time and money.

6C6. Controllers and actuators

If a missile wanders off its proper course, this fact will be detected by the sensing mechanism previously described. The computer within the guidance system will evaluate the information provided by the sensing mechanisms, determine the direction and magnitude of the error in missile course or position, and produce a suitable error signal output.

At this point, the functions of the guidance and control systems overlap. The primary purpose of the control system is to correct errors in the attitude of the missile. The primary purpose of the guidance system is to correct errors in the missile flight path. Both types of error are corrected in the same way: by moving the missile flight-control surfaces. Movements of these surfaces are governed by the same controllers and actuators, regardless of whether the error signal is developed by the guidance or the control system.

Controllers include such devices as relays, solenoids, magnetic transfer valves, and amplidynes. The actuators that apply power to the control surfaces may be electric, hydraulic, pneumatic, or a combination of these. Both controllers and actuators were described in chapter 5.

6C7. Feedback systems

The final section of a guidance system is known as a "feedback" or "follow-up" unit. This unit measures the position of the flight control surfaces in relation to the reference axis of the missile, and compares this value with the error signal generated by the computer.

Without the follow-up signal, there would be nothing but the varying air pressure to prevent the flight control surfaces from swinging to their maximum limits any time the sensor caused an error signal to be generated. By using feedback, the deflection of the flight control surface can be made proportional to the size of the error. The feedback loop thus gradually returns the flight control surfaces to neutral as the error is corrected.

To accomplish these results, the feedback signal is used to oppose the error signal. When the feedback signal becomes as large as the error signal, no further deflection of the flight control surface takes place because the two signals are equal and opposite, and their sum is zero.

If the error signal voltage is large, a large deflection of the flight control surface can take place before the feedback signal voltage becomes strong enough to exactly equal the error signal.

As the missile approaches the desired course, the error signal becomes less than the feedback signal, and the resultant voltage difference reverses polarity. The reversal in polarity moves the flight control surfaces in the opposite direction until they are in neutral. This action is smooth and rapid, and cannot be duplicated by systems that use ON-OFF switching.

Figure 6C4 shows the relationship between the follow-up and error signals, and shows how the flight path is smoothed by combining these signals. Note how much smoother the lower path is than the upper path, which uses the error signal alone.

The discussion of feedback loops completes the basic discussion of the individual stages of a missile guidance system which is shown in block form in figure 6C5.

You should remember that block diagrams may vary as to form of presentation, but the final results will be the same. Block diagrams are related to outside factors as well as those inside the missile. By keeping these facts in mind, you will later be able to see how the reference unit may refer to a ground base unit that is setting up reference points. The computer sections may or may not be in the missile.

D. Types of Guidance Systems

6D1. Preset guidance

The term PRESET completely describes one guidance method. When preset guidance is used, all of the control equipment is inside the missile. This means that before the missile is launched, all information relative to target location and the trajectory the missile must follow to strike the target must be calculated. After this is done, the missile guidance system must be set to follow the course to the target, to hold the missile at the desired altitude, to measure its air speed, and at the correct time, cause the missile to start the terminal phase of its flight and dive on the target.

A major advantage of preset guidance is that only limited countermeasures can be used against it. One disadvantage is that after the missile is launched, its trajectory cannot be changed from that which has been preset at the launch point.

6D2. Command guidance

The term COMMAND is used to describe a guidance method in which all guidance instructions, or commands, come from sources outside the missile. To receive the commands, the missile contains a receiver that is capable of receiving instructions from ground stations or from another aircraft. The missile receiver then converts these commands to guidance information, which is fed to the sections following the sensor unit.

We will list several command guidance systems and briefly describe them. Other chapters in this book will describe these systems in more detail.

HYPERBOLIC SYSTEM. Missile trajectories follow many types of curves. Most of the curves that are followed are determined by the position of the missile in relation to the target position. However, one type of

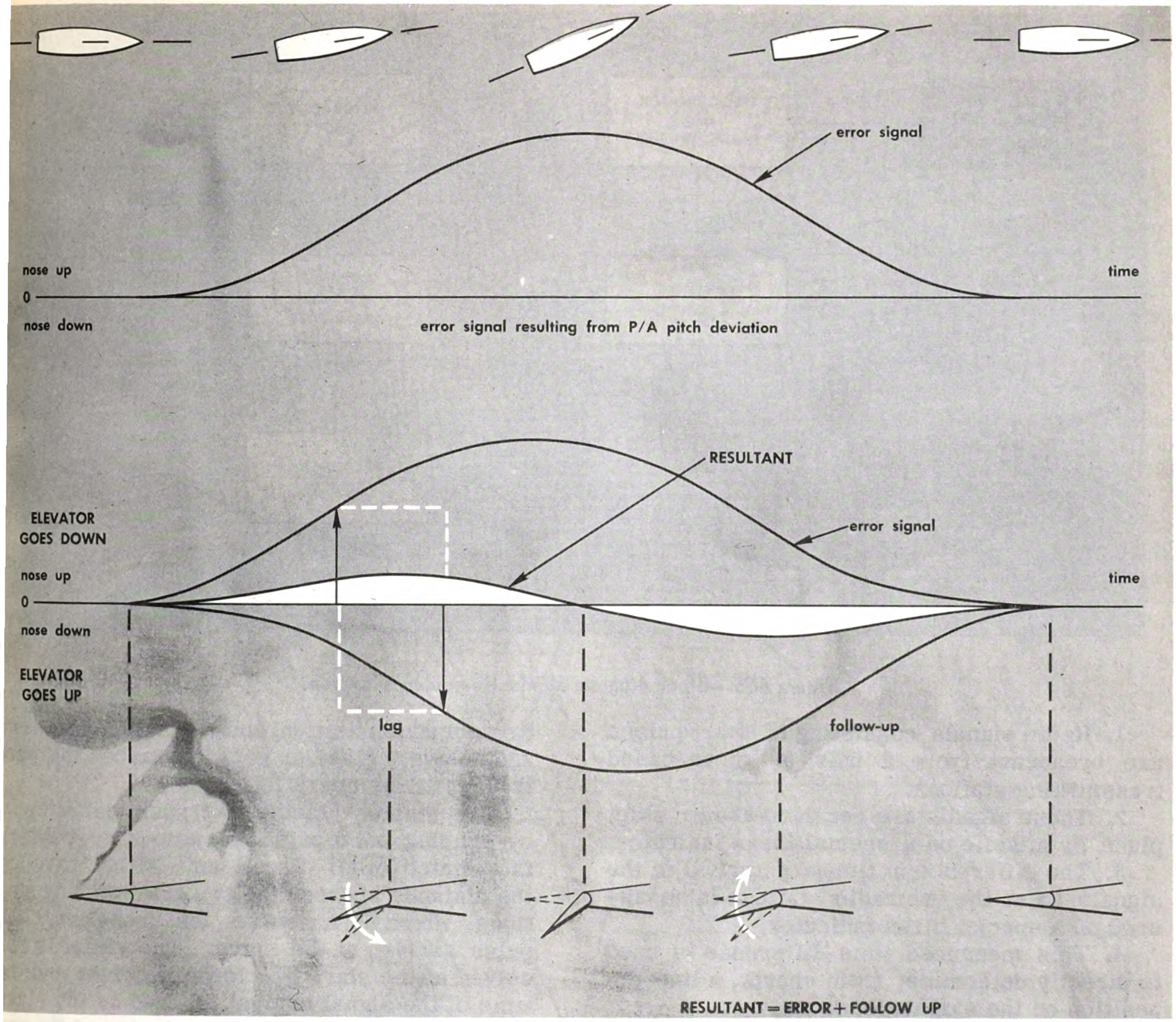

Figure 6C4.—Relationship of follow-up to error signal.

exactly predicted path is a hyperbolic course laid out by a loran-type system.

LORAN PRINCIPLE. A loran system is a modern electronic aid to navigation. The name "loran" was derived from the words "LOng RAnge Navigation." The effective range of loran is as much as 1400 miles at night and about 750 miles during the day. The accuracy is comparable to that which can normally be expected from good celestial observations.

Figure 6D1 shows how hyperbolic lines-of-position are generated by synchronized transmitters separated by several miles.

A navigator can think of loran as a fairly new method of determining lines-of-position. These loran lines can be compared with other loran lines, with sun lines, star lines, soundings, radar range circles, or bearings, to provide navigational fixes.

Loran lines are fixed with respect to the earth's surface, and their determination is not dependent on a compass, chronometer, or other mechanical device. The signals are on the air and available 24 hours per day, and cover the major part of the seas and oceans of the world.

Loran operates on the following principles:

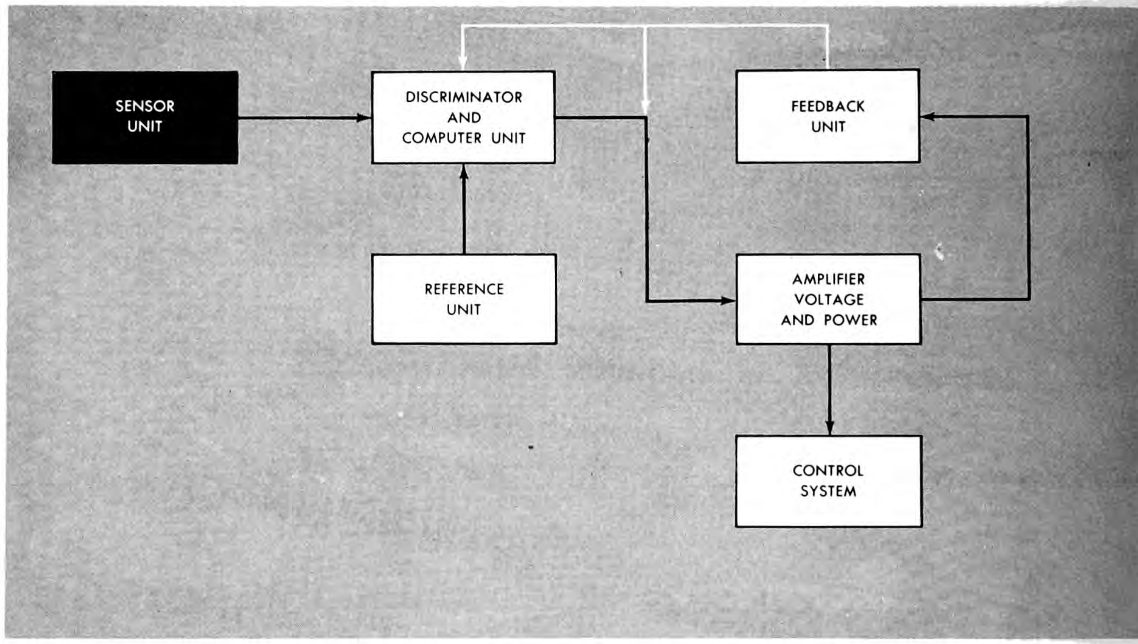

Figure 6C5.—Block diagram of missile guidance system.

1. Radio signals consisting of short pulses are broadcast from a pair of shore-based transmitting stations.

2. These signals are received aboard ship, plane or missile on a special loran indicator.

3. The difference in times of arrival of the signals from the two radio stations is measured on a special loran indicator.

4. This measured time-difference is used to directly determine, from charts, a line-of-position on the earth's surface.

5. Two lines-of-position, determined from two pairs of transmitting stations, are crossed to obtain a loran fix.

Since radio signals travel at a constant speed, a direct relationship exists between the time of travel and the distance covered during that time. Therefore, a measure of time, is, in essence, a measure of distance. With these features it is easy to see how loran could be used as the basis for a missile guidance system.

The transmitters are fixed components of a loran system. Because loran is concerned with the measurement of radio signals from two different sources, the transmitters operate in pairs. The function of each station in a loran pair is somewhat different from that of its companion station, and the names "master" and "slave," given to each describes the part it plays in the operation.

The master starts the transmission cycle by sending out a pulse of radio energy which is radiated in all directions. After traveling the distance between the two transmitting stations, which is known as the "baseline," the pulse arrives at the slave. The signal is received at the slave by a loran receiver and the time of the signal arrival is used by the slave as a reference for the transmission of its own signal.

After the slave has sent its pulse, the whole process is repeated again and again.

If loran is to be used as a form of command guidance, the sensor in the missile must be suitable for loran use. A suitable receiving system is described in chapter 7.

RADIO COMMAND SYSTEMS. Radio has been used as a guidance link for such purposes as model airplane flying, steering model boats and cars, controlling target drones, and even for maneuvering old battleships during bombing tests. Therefore, when the question of command guidance for missiles came up, radio was among the first methods used. But once a radio command system was developed,

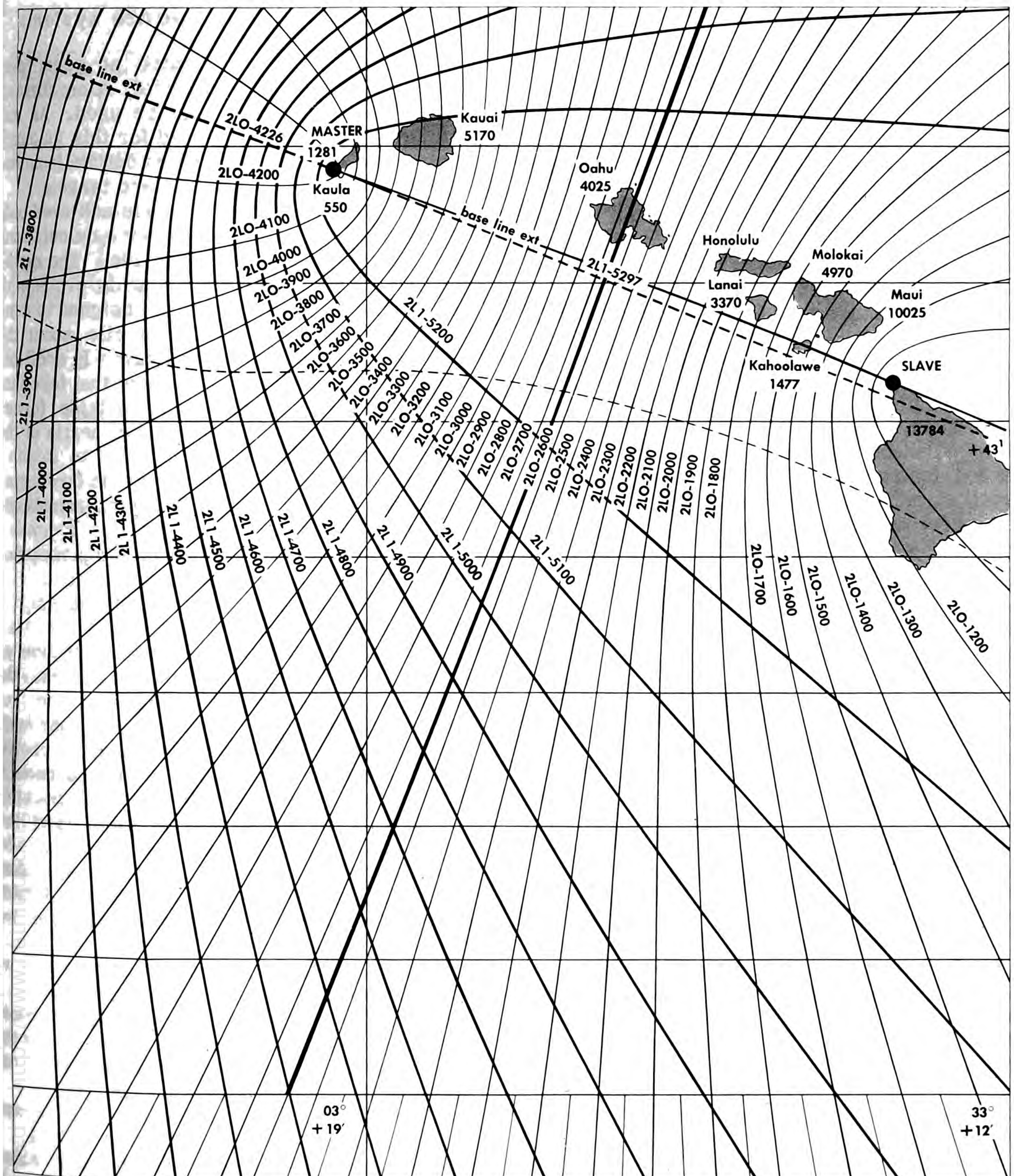

Figure 6D1.—Hyperbolic lines-of-position generated by two transmitters.

a new problem arose—that of keeping track of the missile when it was beyond the range of normal vision.

Since radar can locate objects not visible by ordinary means, it can be used for missile tracking. The radar set transmits a highly directional pulse, which is reflected by objects within the lobe of energy sent out from the radar antenna. The pulse is returned to the radar set as a reflection. The time between the sending of the pulse and the arrival of the reflection can be accurately measured. From this time measurement, the distance to the object can be determined. The course of a missile can be followed by radar, and course correction signals sent by radio.

However, even with radar tracking and radio guidance, it is difficult to keep the missile on course. Consequently, other items have been added to the guidance system.

In order to keep track of the missile, a plotting board can be used. The missile position is determined at intervals, and its successive locations marked (plotted) on a chart. By drawing a line through the successive plots, the missile course can be determined. Once a part of the course has been plotted, the information can be fed into a computer which will determine the desired course for the remainder of the flight.

Since missiles travel at high speeds, mechanical plotters and computers are used in modern systems. Commands to correct the missile course can be transmitted as soon as a deviation from the required course is detected.

The use of radio for command guidance of high-speed missiles makes it necessary to use a transmitter that can do more than send simple ON-OFF pulses. Otherwise, a separate transmitter would be required for each control function. This would require several radio channels for each missile.

In order to get simultaneous operation of several functions, modulated transmissions are used. To overcome other difficulties, frequency modulation using pulse techniques, and radar with pulsed modulation, have been found suitable. The various modulation systems are described in other chapters of this book, along with the advantages and disadvantages of each method.

6D3. Navigation guidance systems

When targets are located at great distances from the launching site, some form of navigational guidance must be used. An example, which shows the need for this guidance method, is the Polaris, which can be launched from a submarine against inland targets.

Accuracy at long distances is achieved only after exacting and comprehensive calculations of the flight path have been made. The mathematical equation for a navigation problem of this type may contain factors designed to control the movement of the missile about the three axes—pitch, roll, and yaw. In addition, the equation may contain factors that take into account acceleration due to outside forces (tail winds, for example) and the inertia of the missile itself.

In this section, we will describe three systems that may be used for long-range missile guidance.

INERTIAL GUIDANCE. The simplest principle for guidance is the law of inertia. In aiming a basketball at a goal, you attempt to give the ball a trajectory that will terminate in the basket. In other words, you give an impetus to the ball that causes it to travel the proper path to the basket. However, once you have let the ball go, you have no further control over it. If you have not aimed correctly, or if the ball is touched by another person, it will miss the basket. However, it is possible for the ball to be incorrectly aimed and then have another person touch it to change its course so it will hit the basket. In this case, the second player has provided a form of guidance. The inertial guidance system supplies the intermediate push to get the missile back on the proper trajectory.

A simple inertial guidance system is shown in figure 6D2. This system is designed to detect errors in the trajectory by measuring the lateral and longitudinal accelerations during the missile flight. To do this, two main channels are used—one for direction and the other for distance.

As shown by figure 6D2, there is some similarity between the two channels. Each contains an accelerometer, which is used to detect missile velocity changes without the need for an external reference signal. The acceleration signals are fed to a computer, which continuously produces an indication of

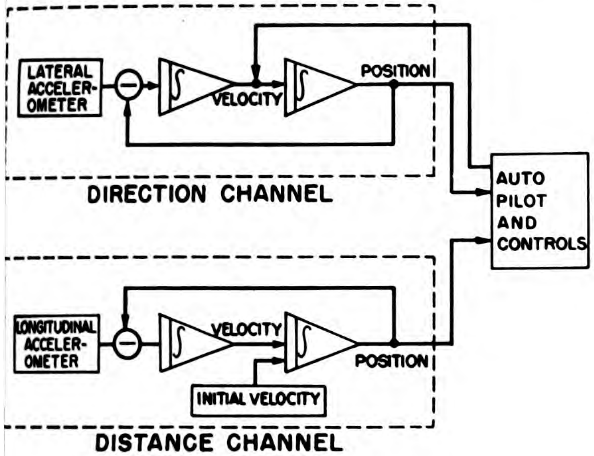

Figure 6D2.—Inertial guidance system.

lateral or longitudinal distance traveled as a result of acceleration. This is accomplished by integrating missile acceleration signals to obtain a missile velocity signal. When the velocity signal is integrated, the result is missile distance traveled. This method of double integration is built into each channel.

An accelerometer, as its name implies, is a device for measuring the force of an acceleration. In their basic principles, such devices are simple. For example a pendulum, free to swing on a transverse axis, could be used to measure acceleration along the fore-and-aft axis of the missile. When the missile is given a forward acceleration, the pendulum will tend to lag aft; the actual displacement of the pendulum from its original position will be a function of the magnitude of the accelerating force. Another simple device might consist of a weight supported between two springs. When an accelerating force is applied, the weight will move from its original position in a direction opposite to that of the applied force. The moving element of the accelerometer can be connected to a potentiometer, or to a variable inductor core, or to some other device capable of producing a voltage proportional to the displacement of the element.

If the acceleration along the fore-and-aft axis were constant, we could determine the speed of the missile at any instant simply by multiplying the acceleration by the elapsed time, in accordance with the formula

$$v = at$$

However, the acceleration may change considerably over a period of time. Under these conditions, integration is necessary to determine the speed. This operation in effect makes it possible to multiply a fixed quantity (such as elapsed time) by a varying quantity (such as acceleration). This can be done by dividing the elapsed time into a large number of "increments" of time. If we multiply acceleration by time for each such increment, the result will show the increment of speed during that time. If we add up all the increments of speed, the sum will be a very close approximation to the speed of the missile.

The actual electronic circuits used for integration are rather complex, but here again the basic principle is simple. In one type of integrator the input consists of a series of evenly spaced electrical pulses representing increments of time. The amplitude of each pulse is controlled by the accelerometer, so as to represent the instantaneous value of acceleration. Thus the quantity of electricity in each pulse represents an increment of speed. The pulses are passed through a rectifier (so that no current can flow in the opposite direction) and stored in a capacitor. The capacitor will, in effect, add up all of the input pulses. Thus the voltage across the capacitor will, at any given instant, provide an indication of missile speed at that instant.

If the missile speed were constant, we could calculate the distance covered simply by multiplying speed by time. But because the acceleration varies, the speed also varies. For that reason, a second integration is necessary.

An acceleration may, of course, be applied to the missile in any direction. Thus, if the missile is to determine its own position at any given instant, two accelerometer channels are necessary. For any given acceleration, one of these measures the component of force along the fore-and-aft missile axis; the other measures the component across that axis.

The distance and direction channels are identical in operation. The output voltage of the first integrator indicates the missile velocity. The output voltage of the second integrator is proportional to the distance the missile has traveled.

In order to determine when the missile has reached the target, the distance traveled by the missile must be compared to the known

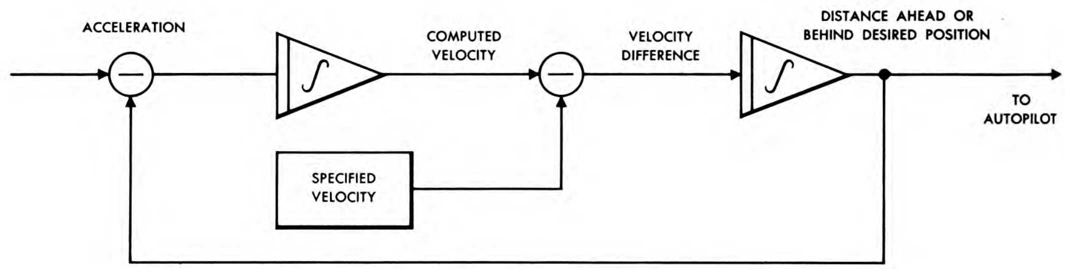

Figure 6D3.—Specified velocity reference.

distance from the launch point to the target. This comparison may be made by setting up a comparison voltage, representing the entire distance the missile is to travel, as an initial condition at the time of launching. This voltage is added, with opposite polarity, to the output of the second integrator. As the missile approaches the target, the output voltage of the distance channel decreases. At zero volts output, the destination has been reached.

This method of determining when the missile reaches the target has the disadvantage of requiring large integrator and comparison voltages if long distances are involved. However, this disadvantage may be overcome by specifying short distance comparison points throughout the flight. The specification of comparison points can be done by a recorder carried in the missile.

Another method that may be used to hold down required voltages for long trips is to specify the velocity and use that as a reference condition on the first integrator output. This method is shown in block diagram form in figure 6D3.

When this system is used, any error above or below the specified velocity is fed to the second integrator. The resultant output is proportional to the missile error in distance at a given time.

Other information on inertial guidance systems will be given in a later chapter in this book.

CELESTIAL REFERENCE. Navigation by fixed stars and the sun has been practiced for years, and is very dependable.

A missile guidance system which uses celestial reference most likely would be made up of an inertial system supervised by a series of fixes on the sun or stars. The gyro that controls the position of the accelerometers is subject to random drift, and the result is an error that tends to increase with time. The error may be as much as half a mile for a flight that lasts 45 minutes. For longer flights, the error would naturally increase.

One method that may be used to overcome the random drift error involves the use of star sights. The checking is done in much the same manner as a human navigator would check his position by observing an object, such as a star, having a known position.

To make the check, an automatic sextant is mounted on a platform in the missile so that it can be turned on elevation and azimuth axes. An automatic sextant is shown in figure 6D4.

The position data is recorded on a tape, which is placed in the missile prior to launching. The tape is pulled through a "reader" head, which contains a series of contacts that are actuated by holes in the tape. The motor that pulls the tape receives its voltage from a timing circuit. Thus the rate at which the tape is pulled through the "reader" is carefully controlled.

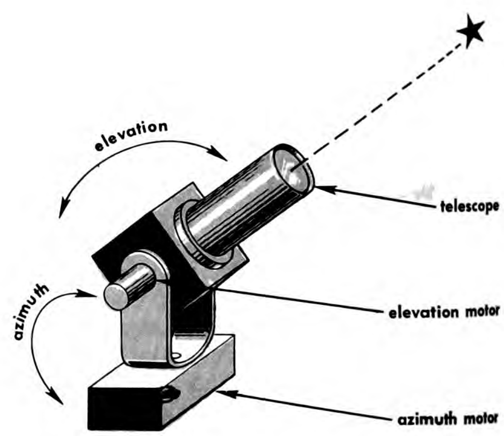

Figure 6D4.—An automatic sextant.

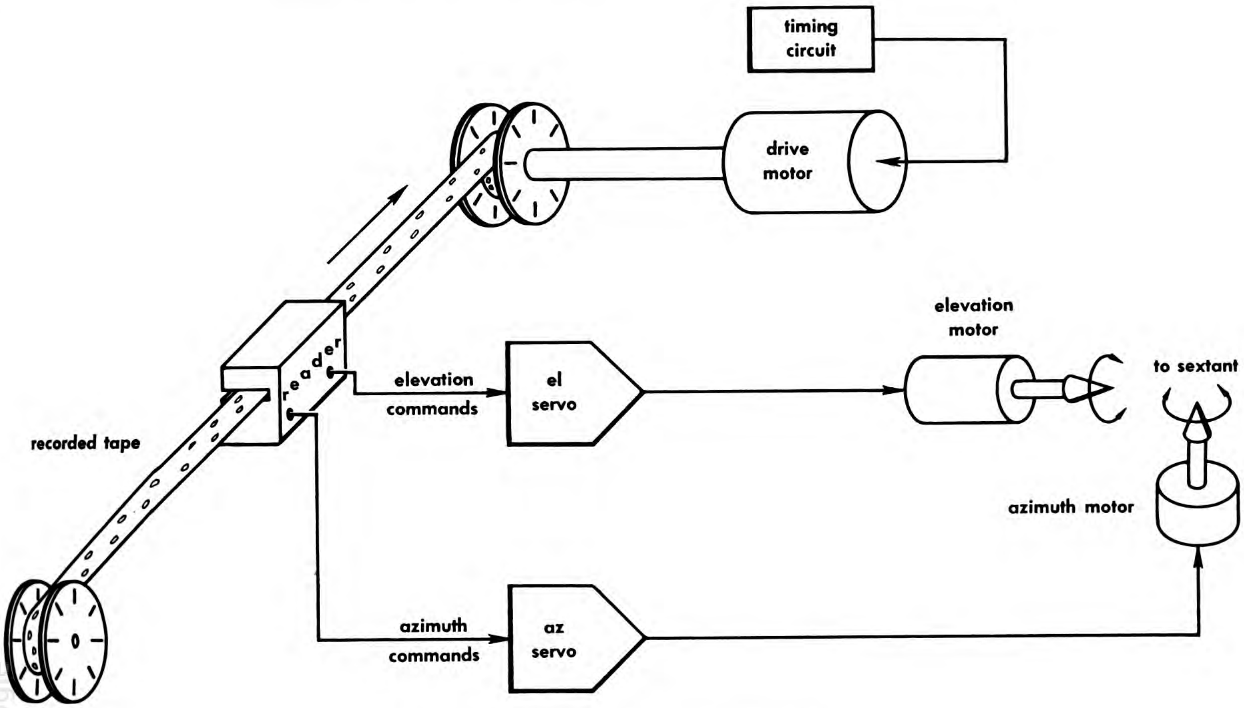

Figure 6D5.—Sextant positioning system.

Figure 6D5 shows a sextant positioning system in block form. Note that the elevation servo generator and the azimuth servo generator both receive signals from the tape reader. The generators are connected to servo motors. The shafts of these motors are mechanically connected to the sextant positioning gears, so that the sextant position is actually controlled by the information on the tape.

The position of the sextant is checked by a section called the STELLAR ERROR DETECTION CIRCUIT, which determines whether or not the star is centered in the telescope field. If the star is not centered in the field, an error signal is generated and processed to show the amount of sextant error. The error detection circuit is shown in block form in figure 6D6.

The outputs of this circuit are voltages that are proportional to the missile error in pitch, roll, and yaw. The output voltages are obtained by feeding the starlight picked up by the sextant to a mechanical scanner unit. This unit contains a chopper which modulates the light beam at a given rate. The modulated light beam falls on a phototube, causing the phototube output to vary in proportion to the light intensity.

The phototube output is amplified, rectified, and fed to a resolver that compares the rectified photocell voltage to a fixed reference voltage. The resolver output consists of two error signals, one in azimuth and the other in elevation. The azimuth error is fed to the yaw comparator along with the azimuth commands from the tape. The resultant voltage, obtained by comparing the error and command signals, is the yaw error signal.

The elevation error signal from the direction resolver is fed to the pitch and roll resolver where it is compared to the tape signal. The output of the resolver is divided into two voltages—the pitch error signal and the roll error signal. It is not possible to obtain proportional control with this system because of the delay in signals getting through the circuits, and damping by the rate function. However, the system does tend to return the missile to the correct course as soon as possible without over-control oscillations.

TERRESTRIAL REFERENCE. Three characteristics of the earth's magnetic field that are useful for missile guidance are (1) lines of equal magnetic deviation, (2) lines of equal magnetic inclination, and (3) lines of equal magnetic intensity. Refinements of the

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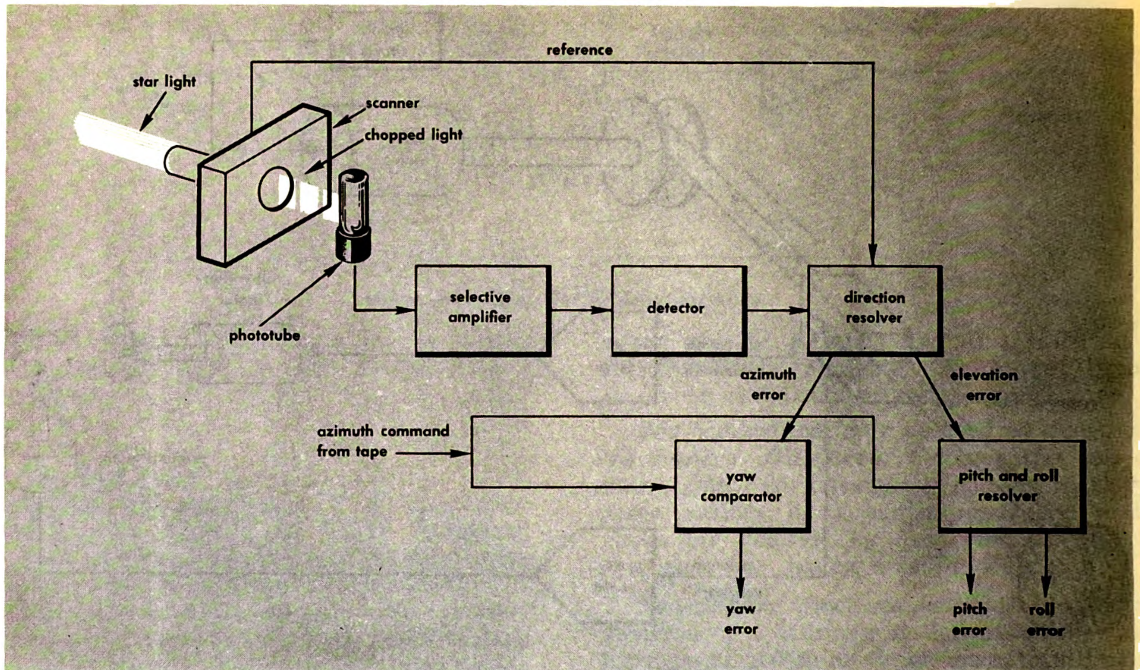

Figure 6D6.—Stellar error-detection circuit.

magnetic compass, such as the flux valve, can be used in missile guidance. A complete magnetic guidance system is shown in block diagram form in figure 6D7.

The flux valve consists of primary and secondary windings on an iron core. The primary is supplied with a-c of a fixed voltage and frequency. When no external magnetic field is present, the device acts as a simple transformer; the frequency of the secondary voltage is the same as that of the input voltage. But when an external field is present, it will alternately add to and subtract from the field generated by the primary current, during successive half-cycles. As a result a second harmonic, at twice the input frequency, is superimposed on the output voltage. If the flux valve is properly aligned with the external magnetic field, the amplitude of the second harmonic voltage will be proportional to the strength of that field.

The magnetic guidance system represented in figure 6D7 uses three flux valves; in the diagram they are called the axial orient coil, the transverse orient coil, and the detector coil. The three flux valves are rigidly secured together, with axes mutually perpendicular. The outputs of the axial and transverse flux valves are used to operate servo systems that control the position of the three-valve assembly. The effect of these servos is to orient the assembly so that its detector coil is constantly aligned with the earth's magnetic field.

The output of the detector coil consists of the 400-cycle input frequency, combined with the 800-cycle harmonic that results from the action of the earth's magnetic field. This combined output is fed to a filter amplifier that amplifies the 800-cycle voltage, but eliminates the 400-cycle signal. The amplifier output is then fed to a frequency divider, which changes the 800-cycle signal back to a 400-cycle signal suitable for operating the missile control system. The amplitude of this signal will be proportional to the strength of the earth's magnetic field.

A 400-cycle reference voltage can be preset before launching, at a value equal to that resulting from any given strength of the earth's

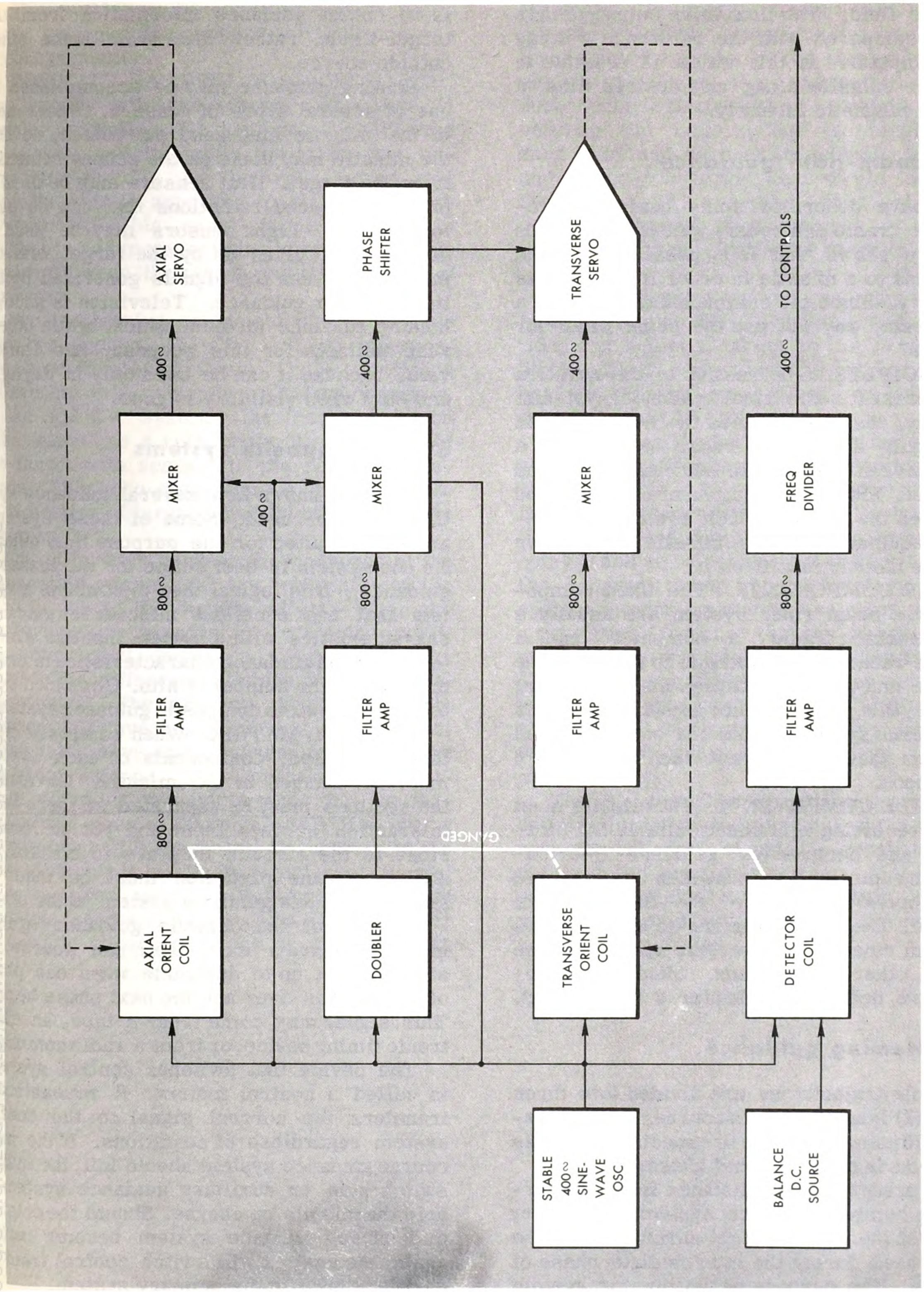

Figure 6D7.—Magnetic system.

magnetic field. The flux valve output voltage can be compared with the reference voltage by a computer. In this way it is possible to guide the missile along any desired line of constant magnetic intensity.

6D4. Beam-rider guidance

We have described some basic electromagnetic (radio and radar) guidance methods and have shown that it is possible to send commands to a missile in order to correct its trajectory. Since the commands are sent on a radio beam, why not use the beam itself for guidance?

PRINCIPLES. The answer to the question is the present beam rider guidance systems. Basically, the system uses the beam pattern of a highly directional radar antenna as a track between the missile launching point and the target. Electronic equipment on the ground modulates the beam in such a way that electronic equipment in the missile can derive guidance instructions from it.

FIXED COMPONENTS. The fixed components of a beam rider system are usually a target-tracking radar, a computer, and a guidance radar. It is possible to combine the guidance and tracking function into one beam. However, this method is not as satisfactory as a two-beam system. Both the one-beam and two-beam systems are described in chapter 8 of this book.

MISSILE COMPONENTS. The missile must contain receiving equipment suitable for picking up and deciphering guidance information. This information must then be converted to appropriate motion of the flight control surfaces. The Navy's surface-to-air missiles are beam riders. However, the system is also used in other applications. Missile components are detailed in chapter 8 of this text.

6D5. Homing guidance

Missile trajectories are divided into three phases (1) launch, (2) midcourse, and (3) terminal. Homing guidance is especially suitable for use during the terminal phase.

At a predetermined distance from the target, the homing guidance system takes over control of the missile flight surfaces from the system used during the intermediate phase of guidance. The purpose of the homing system is to obtain guidance information from the target itself, rather than from some other outside source.

Homing guidance may be accomplished by one of several types of sensors. Radar sets in the missile may send out pulses, so that the missile may home on the echoes returning from the target. Heat sensors may be used to pick up infrared radiations that can be used for homing. Light sensors may be used to pick up light given off by the target, and the missile can use the signals generated by the light cell for guidance. Television is another homing guidance medium which, while otherwise suitable for this purpose, has limited value because it can be used only in daylight, and only when visibility is good.

6D6. Composite systems

We have shown how several guidance systems may be used. Some of these systems are better suited for one purpose than others. No one system is best suited for all phases of guidance. It is logical then to combine a system that has excellent midcourse guidance characteristics with a system that has excellent terminal guidance characteristics in order to increase the number of hits. Combined systems are known as composite guidance systems.

CONTROL MATRIX. When composite systems are used, components of each system must be carried in the missile. Obviously, the sections must be separated so there is no interaction between them and yet be located close to the circuits they are to control. In addition, some provision must be made to switch from one guidance system to the other.

Control of the missile guidance system may come from more than one source. A signal is set up to designate when one phase of guidance is over and the next phase begins. This signal may come from a tape, an electronic timing device, or from a radio command.

The device that switches control systems is called a control matrix. It automatically transfers the correct signal to the control system regardless of conditions. If the midcourse guidance system should fail, the matrix switches in an auxiliary guidance system to hold the missile on course. Should the original midcourse guidance system become active again, the matrix will switch control from the auxiliary back to the primary system.

The matrix can be considered as an automatic guidance switchboard, or guidance sequence computer.

VELOCITY-DAMPING DOPPLER RADAR. One homing guidance system makes use of doppler principles. No doubt you have listened to a train whistle while the train was approaching rapidly. As the train moved past you, its whistle appeared to change in pitch (frequency). This same doppler effect is present in radar waves when there is relative motion between the target and the antenna of the radar.

Doppler homing equipment can be divided into two groups—FM-CW doppler systems, and pulse doppler systems. There are major differences in the circuitry of the two systems. In the FM-CW system, the frequency of an echo signal has a relationship to the speed of the target with respect to the receiving antenna. This echo signal can be converted into an indication of target velocity with respect to the missile.

The difference between the frequency of the transmitted signal and the frequency of the echo is due to the doppler effect. When the two signals are mixed in an electronic circuit, the circuit will develop a "beat" frequency equal to the difference between the two signal frequencies. The beat note developed in this manner will have a pitch that is proportional to the relative velocity between the target and the radar antenna. To eliminate the possibility of homing on objects other than the target, a band-pass filter (which will pass only a narrow band of frequencies) is inserted in the control circuit to eliminate interfering signals.

A receiver which is automatically tuned over the frequency range passed by the filter is used to choose and lock on a target. An automatic frequency control (AFC), in the missile receiver, maintains the receiver on the selected target. At the closest approach point to the target, the doppler shift becomes zero because there is then no relative motion between the missile and the target. The zero shift can be used to detonate a missile and destroy a target that would otherwise be missed. This system does not provide a means of range measurement. If this feature is desired, additional circuits are required.

A pulse doppler system performs the same functions as an FM-CW system and, in addition, can select a target by its range. Like other pulsed radar systems, it has greater operating range for a given average power output than a CW system.

The guidance control signals are sent as a series of timed pulses. The receiving system in the missile must contain circuits that will match the transmitted pulses in both pulse timing and r-f cycles. The matching is accomplished in electronic circuitry known as the coherent pulse doppler system. In this system the transmissions are short pulses at a repetition frequency that can be continuously varied. Low-intensity power, which is used to obtain phase coherence between successive pulses, is generated by the stabilized local oscillator. A duplexer provides low-impedance paths to keep the oscillator energy in the desired circuits.

The stabilized oscillator also provides a suitable local oscillator signal which is mixed with the receiver signals to generate a receiver intermediate frequency. The doppler receiver contains a type of filter, called a velocity gate, which filters out all undesired doppler frequencies.

CHAPTER 7

COMMAND GUIDANCE

A. Introduction

7A1. General

For maximum effectiveness, the first missile fired at a target should strike that target. Cost, size, and the necessity for surprise prohibit the firing of ranging shots (as was done with gun fire).

To strike the target on the first shot, the trajectory of the missile must be accurately controlled. This control is necessary because forces, natural or otherwise, can cause the missile to deviate from its predetermined course. Even though it functions perfectly, a missile without accurate guidance may miss a selected fixed target by several miles. Moving targets can take evasive action; without guidance, the missile would be unable to compensate for this action. Therefore, an accurate, fast-acting guidance system is of prime importance.

7A2. Definitions

The various systems of missile guidance were discussed briefly in chapter 6. This chapter deals with COMMAND GUIDANCE. The name means that intelligence (commands) is transmitted from an outside source while the missile is in flight. Current missiles controlled by command guidance include Regulus, Bullpup, and Nike.

A command guidance system incorporates two links between the missile and the control point.

One, an INFORMATION LINK, enables the control point to determine the position of the missile; the other, the COMMAND LINK, makes it possible for the control point to correct any deviations from the desired path.

7A3. Purpose and applications

The purpose of any guidance system is to secure direct hits on a selected target. Perfect performance is difficult to obtain because of natural disturbances and, in wartime, enemy countermeasures. However, because command guidance makes it possible to change the flight path of the missile by signals from the control point, most of these difficulties can be overcome. It is reasonable to assume that command guidance can be used whenever it is possible to accurately determine the position of the missile during its flight. (But command guidance is not limited to missiles alone. It may be used for remote control of target drone planes or even ships.)

7A4. Basic principles

When command guidance is used, a ground, shipboard, or airborne station determines the position of the missile by radar tracking equipment or other means. It determines the error, if any, between the actual position of the missile and the desired position. It then sends out control impulses (commands) to bring the missile to the desired course.

If the flight path is long, and a large part of the path is over friendly territory or waters, several stations might track the missile as it comes into their range. These stations would then send commands to the missile to correct any deviations from the desired course.

7A5. Information links

The use of command guidance requires an accurate knowledge of the missile position, since all guidance comes from outside the missile. This knowledge is obtained through information links. The accuracy and dependability of the information link determines to a great extent the over-all accuracy of the complete system.

The information link enables the control point to determine the amount of error existing between the actual position of the missile and the desired position. Once this is known, correction signals can be sent to the missile.

Information links may use optical or electronic observation methods.

OPTICAL OBSERVATION. The optical, or visual, command guidance system has limited value, since the missile must always be visible from the command station. Such a system might use the unaided eye, telescopes, or optical rangefinders. But these devices are not

ffective at long range; and smoke, fog, clouds, r darkness make them useless.

ELECTRONIC OBSERVATION. Much effort as been expended to develop an accurate and ependable electronic information link. A numer of electronic systems have been designed nd tested. The limitations of each system ave been determined, and continuing efforts re being made to improve the most promising ystems. Some electronic information links ill be listed here, and more complete infor- ıation on individual systems will be given ıter in this chapter.

'A6. Command links

The equipment used to send commands to a ıissile may be compared to a radiotelephone ircuit between a piloted plane and a ground tation. Instead of voice communications, the instructions are sent as a single pulse or a series of spaced pulses. The pulses may be modulated or unmodulated, depending on the complexity of the system in use.

TRANSMITTERS. Early target drone command transmitters were simple one-tube units that sent out a pulse when keyed by the operator. This system made it possible to control the rudder. But to control engine speed and altitude, additional transmitters tuned to other frequencies were required. As a result, the system became so large and complex that it was unsuitable. Consequently, work was started on a simpler, more reliable transmitter that would reduce the number of radio frequency (RF) channels needed for command guidance. The result of this work is the modern command guidance transmitter, which is similar to any medium power PM (phase modulated) transmitter. A block diagram is shown in figure 7A1.

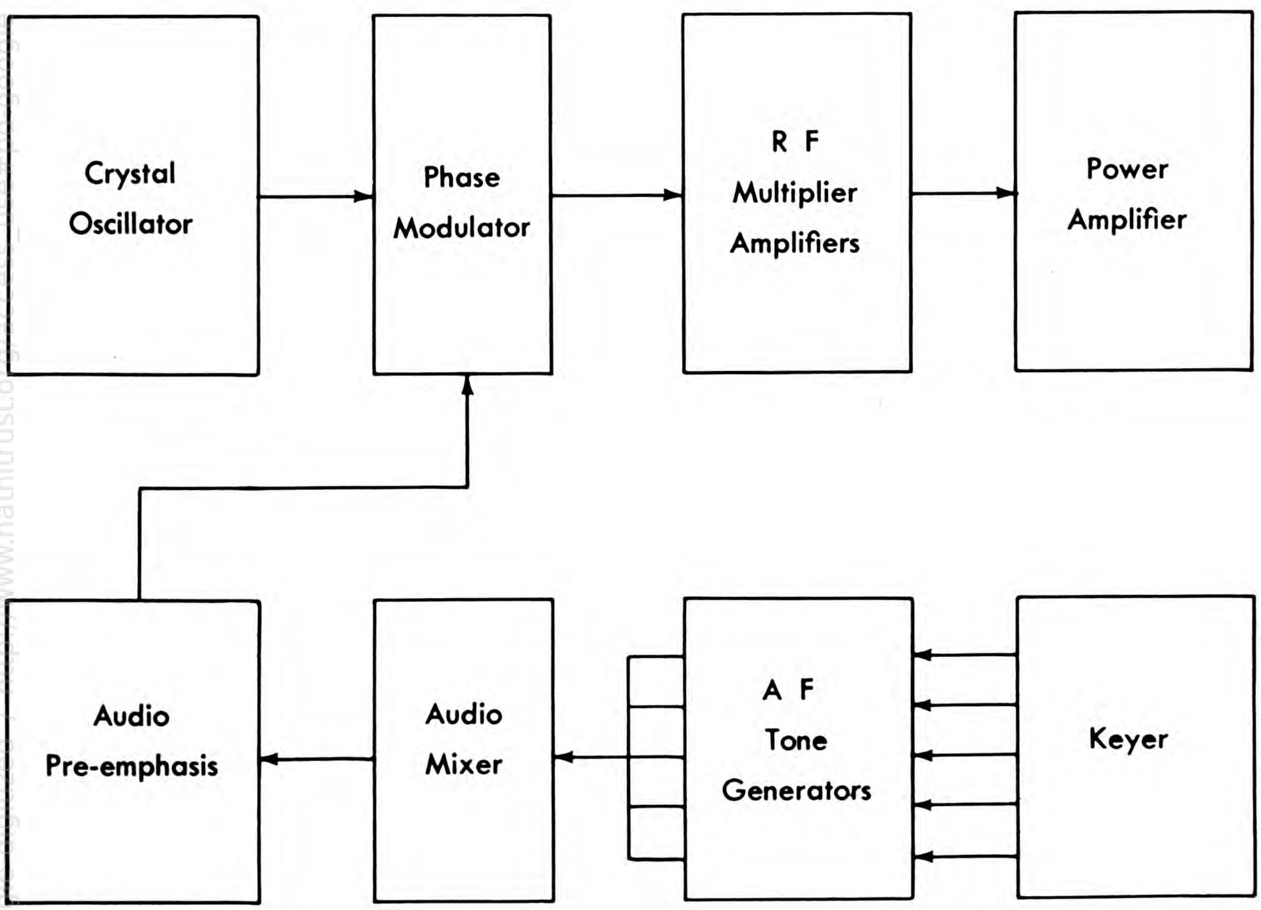

Figure 7A1.—Block diagram of a phase modulated command transmitter.

The transmitter uses a crystal-controlled oscillator for frequency stability and accuracy. Accurate frequency control is of prime importance since the command receiver in the missile is tuned to the command frequency before the missile is fired, and the receiver tuning cannot be changed while the missile is in flight. Therefore, the transmitter frequency must remain stable or the command link will be lost.

The output of the crystal oscillator is built up by RF amplifier stages. Some of these stages operate as frequency multipliers, but the output stage operates as a straight-through RF power amplifier.

TRANSMITTER MODULATION. The use of PM results in considerable saving of space, power, and cost, since modulation takes place at a low level and requires less audio power than does high level AM.

Modulation is in the form of tones that are generated by tone generators. Each generator may be keyed separately or in combination with others. The tone generator outputs are fed to an audio mixer circuit and, as a result of the mixing, a composite tone appears at the output of the mixer stage.

The composite tone is fed to an audio pre-emphasis network. This network builds up (emphasizes) the higher audio frequency components of the composite signal. This action is desirable because atmospheric noise usually consists of high frequency components. Pre-emphasis is used only on the high frequency tones, and thus causes the signal-to-noise ratio to remain more constant throughout the audio range.

As shown in figure 7A1, the composite tone from the pre-emphasis network is fed to the phase modulator stage, which is connected between the crystal oscillator and the first frequency multiplier stage.

In order to understand how phase modulation (PM) takes place it is necessary to remember that the frequency of an alternating current is determined by the rate at which its phase changes. If the phase of the current in a circuit is changed, there is an instantaneous frequency change during the time that the phase is being shifted. The amount of frequency change, or deviation, depends on how rapidly the phase shift is accomplished. It also depends on the amount of phase shift. In a properly operating PM system, the amount of phase shift is proportional to the instantaneous amplitude of the modulating signal. The rapidity of the phase shift is directly proportional to the frequency of the modulating signal. Consequently, the frequency deviation in PM is proportional to both the amplitude and frequency of the modulating signal. Thus the crystal oscillator output signal is varied in both amplitude and phase by the modulating signal.

The RF section of the transmitter operates continuously, but is modulated only when one or more of the tone generators are operated by the keyer section.

RECEIVER. In the beginning, receivers used for remote control were simple one-tube super-regenerative sets. A relay was connected in the plate circuit of the tube; when a signal was applied to the input of the tube, its plate current changed and operated the relay. The closing of the relay contacts activated another circuit which moved the control surfaces.

The disadvantage of this system is that separate receivers are required for each control function. In addition, the superregenerative receiver, in its most sensitive condition, is a low-powered transmitter that could interfere with other receivers in the missile.

But receiver development kept pace with transmitter development, and simple one-tube sets were replaced by superheterodyne receivers. As shown in figure 7A2, these sets are identical to standard frequency modulation (FM) receivers (PM can be picked up by an FM set) up through the discriminator stage. In an FM set, the discriminator stage takes the place of the second detector in an AM superheterodyne.

USE OF TONE CHANNELS. The discriminator output is fed to AF channel selectors and there is one receiver channel selector for each tone the transmitter may send.

The sections of an AF channel selector are shown in figure 7A3. A sharply tuned bandpass filter (one that passes certain frequencies better than others) is at the input of an amplifier stage.

The grid bias of this stage is adjusted so that plate current is cut off when no signal is being fed to the stage. When a signal is applied to the input of the stage, the effective grid bias is reduced to the point where plate current flows. The change in plate current operates the relay; its contacts close, and activate the missile control surfaces.

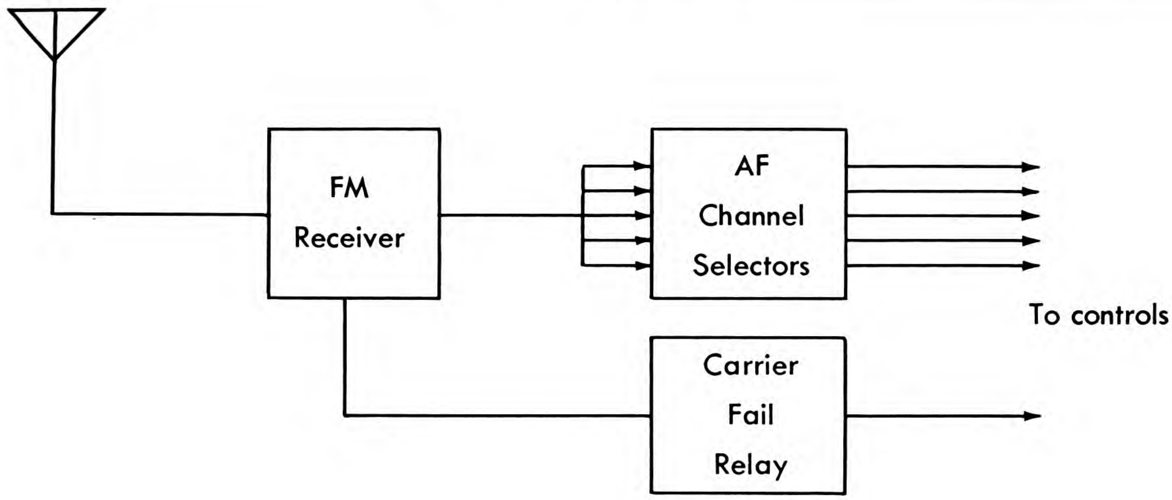

Figure 7A2.—Block diagram of FM command receiver.

Not shown on the receiver block diagram, figure 7A2, is the de-emphasis network, which has opposite characteristics to the pre-emphasis network used in the transmitter. Thus, after passing through the de-emphasis network, the signal has the same characteristics it had before pre-emphasis.

7A7. Types of command guidance

As mentioned previously, command guidance may be exercised by one or more ground stations, shipboard stations, or aircraft. The guidance point influences the type of command guidance used. Since all command systems are subject to enemy jamming of the control circuit, the closer the missile can be launched to the target the better. A shorter time required for the missile to travel from the launcher to the target means less time for the enemy to jam the controls.

Electronic command guidance systems are divided into four principal groups.

TELEVISION GUIDANCE SYSTEM. Television command guidance is well suited for some missions where the control point is in a mother aircraft. The control aircraft can stay out of range of hostile antiaircraft defenses and yet launch the missile reasonably close to the target. Because the target is picked up by the missile camera before the missile is launched from the aircraft, the missile controller in the plane sees the target through the missile camera from the time the target is first picked up until the missile strikes. Because of the close range at the time of firing, the system is quite accurate; and because of the short time between launching and striking, there is less chance of enemy jamming. But this is essentially an optical system, and is not

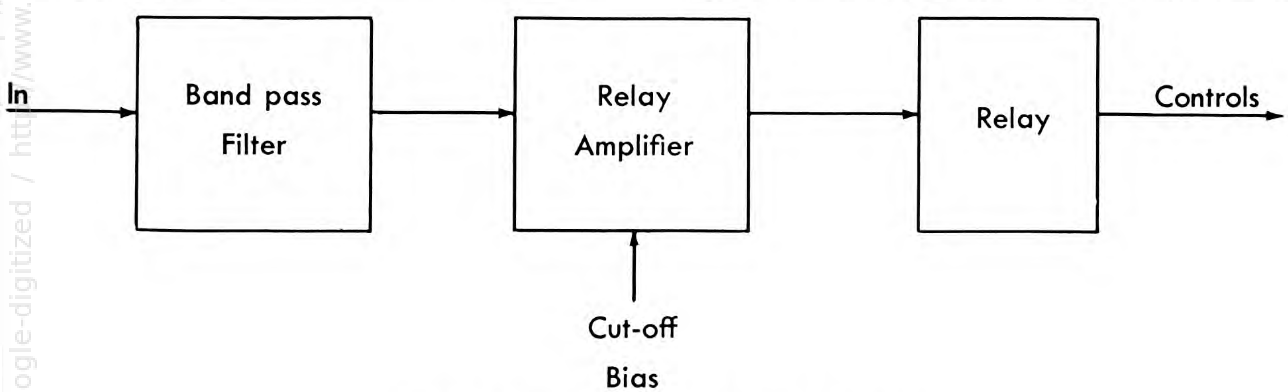

Figure 7A3.—Block diagram of AF channel selector.

suitable for use when the target is obscured by overcast, smoke, fog, or darkness.

RADIO AND RADAR COMMAND GUIDANCE. These two systems are much alike. Each is based on a transmitter at the control point, and a receiver in the missile. The transmitter sends out a carrier wave, which is modulated in accordance with the command signals. The receiver interprets the modulation so that the missile can execute the transmitted commands. The two systems differ in two ways. First, radar operates at a higher frequency. Second, the radio transmitter usually sends out a continuous carrier wave, whereas the radar transmitter sends out its signals in the form of short pulses, with resting intervals between. Since both of these systems are treated in more detail later in this chapter, they will not be described further here.

HYPERBOLIC GUIDANCE SYSTEM. A hyperbolic guidance system can be used for both long and short range missile guidance. This system will be described more fully at the end of this chapter. It consists of master and slave stations that send out low-frequency pulses at constant intervals. The slave station is triggered by the master station, and sends out its pulses a few microseconds after the master pulse is transmitted. These pulses are picked up by receivers in the missile and fed to an automatic computer in the missile. The computer then establishes the missile position by an imaginary line of position set up by the master and slave stations.

B. Radio Command System

7B1. Basic principles

A radio command system contains a means of accurately determining the missile position in relation to the control station, the target, and the desired trajectory. A computer is usually used to determine the error between the actual missile position and the desired position. A command transmitter is located at the control point, and a receiver is contained in the missile. The receiver activates the missile control circuits when it receives command signals from the transmitter. This equipment makes it possible to follow the missile's flight and correct for errors which would cause a miss.

7B2. Applications

Radio command guidance may be used to control missiles aimed at ground targets from surface sites or from aircraft. The controlled missile may be of the surface-to-surface type, surface-to-air type, air-to-surface type, or air-to-air type.

7B3. Limitations

The limitations of a radio command system are imposed by transmission conditions, distance, and enemy countermeasures. Early systems, which used AM tone modulation, had additional limitations. As an example, an interfering signal containing the control-tone frequency would cause the missile control surfaces to act. Often harmonics or sideband frequencies of voice-modulated carriers would upset the whole control system. Obviously, something had to be done if complete control was to be obtained.

The use of PM (phase modulation) eliminated a large part of the voice interference, but manmade interference with PM characteristics could still affect the control system. This disadvantage was overcome by using coded combinations of tone channels. With this system, no control operation can take place unless the proper tones appear at the missile receiver in the correct order and spacing. The adoption of this control method practically eliminates the chance that an interfering signal will duplicate the control combination.

7B4. Launching station components

MISSILE COURSE COMPUTER. Ordinary forms of course determination require a large number of calculations, and considerable time. Since calculations are time consuming, and since speed is an absolute necessity, electronic course computers have been developed.

The computer, located at or near the launching site, performs two functions. First, it determines the course that should be followed by the missile during its flight to the target. It then compares this desired course

with the actual course of the missile, as determined by the tracking radar. Any deviation between the two is instantly detected, and an error signal is sent to the command transmitter keying unit. The keying unit modulates the transmitter with the desired tone and spacing sequence. When these signals are picked up by the missile receiver, the proper control surfaces are activated to bring the missile back on course.

MISSILE TRACKING RADAR. When command guidance is used, the position of the missile in relation to the control point, desired course, and the target area must be known at all times.

Since radar can provide information as to range, elevation, and direction, it is well suited for short- and medium-range missile tracking. In general, missile-tracking radars use the same principles as search, fighter-director, and fire control radars.

Radar ranging is accomplished by time measurement. The range is found by measuring the elapsed time between the transmission of a pulse and the arrival of the echo reflected from the missile. Radar waves travel at the speed of light (186,000 miles per second). The distance to the target is found by multiplying the elapsed time by the speed of the radar wave and then dividing the result by two. The division by two is necessary because the elapsed time includes time out and time back, so that the actual time to the target is one-half the elapsed time.

The time sequence for the radar set is started in the timing generator. The trigger action of the timing generator controls the modulator section, which in turn produces the high-voltage output pulse.

The same trigger pulse is also sent to the range unit, and starts its time-measuring device. After a short, fixed delay, the range unit forms a range gate. The gate is developed by a voltage which is present during a relatively short part of the main time cycle. This voltage is applied to the gain control circuit of the receiver. When the range-gate voltage is present, the receiver gain is high; during the rest of the time cycle, the gain is very low. Thus, when the range gate is "open," signals picked up by the antenna will pass through the receiver; when the gate is "closed," they will not.

A definite time is required for the transmitted signal to reach the missile, and for the reflected signal to return. The total time depends, of course, on the range of the missile. The timing circuits can be adjusted to open the range gate shortly before the reflected signal is due to reach the radar antenna, and to close it shortly afterward. Thus the range gate permits only the echo signals reflected from the missile to pass through the receiver; echoes from other objects will be rejected. The reflected signals, through servo systems, control the position of the radar antenna, so that it will track the missile automatically.

A single antenna is used for both transmitting and receiving. This requires some means for switching the antenna from the transmitter to the receiver, and then back to the transmitter again. The device usually used for this purpose is called a duplexer. The duplexer makes it possible to operate the transmitter and receiver simultaneously, but keeps the powerful transmitter signals from entering the receiver directly.

For missile tracking, a lobing or conical scanning system is used, because accurate angle data cannot be obtained from a single beam on the antenna axis. This type of scanning is described in chapter 8.

Video signals produced by the reflected signal from the missile may be used to modulate the display on a cathode ray tube. The method of modulating the display will depend on the type of indicator used in the radar set. Either the deflection or the intensity of the beam trace may be modulated.

(The student interested in information on basic radar principles is referred to *Supplementary Readings in Fundamental Naval Electronics,* parts I and II, NavPers 10808 and 10809.)

MISSILE PLOTTING SYSTEM. The use of radar for missile tracking makes it possible to obtain information on the missile's elevation, bearing, and horizontal range. This information may be plotted so that personnel controlling the missile will have a complete picture of the operation.

An example of a basic plotting system is shown in figure 7B1. The tracking radar is shown at the left of the drawing, and the plotting board at the right. The boom on the

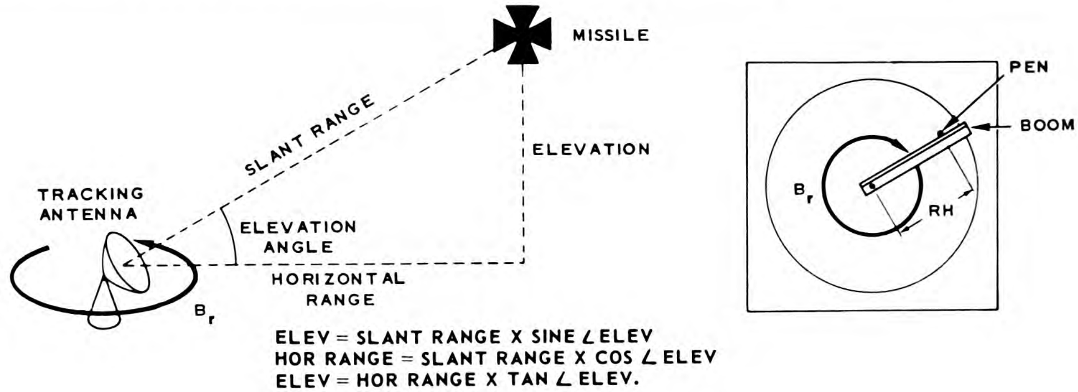

Figure 7B1.—A basic plotting system.

plotting board revolves around a center pivot, and is positioned by the missile bearing data. The tracing pen trolley (mounted on the revolving boom) is positioned by the horizontal range data. The pivot of the boom represents the tracking radar location, and the pen position represents the instantaneous location of the missile.

The radar can provide only slant range, bearing, and elevation angle. The horizontal range data used to position the tracing pen trolley can be obtained from the product of the slant range and the cosine of the elevation angle. The elevation of the missile is the product of the slant range and the sine of the elevation angle (or of the horizontal range and the tangent of the elevation angle). Successive positions of the missile can be marked on the plotting chart at regular intervals, to provide an indication of the missile's course.

COMMAND TRANSMITTER. The transmitter used to send commands to the missile is usually a tone-modulated FM unit. This type of transmitter was discussed earlier in this chapter.

7B5. Missile components

The command guidance equipment components that are built into the missile will be determined by the guidance system being used. The most complex guidance system has a television camera, television transmitter, radio command receiver, and the tone filter equipment built into the missile.

A relatively simple guidance system, so far as total equipment in the missile is concerned, is based on a radar transmitter that sends guidance commands to the missile on the tracking radar beam. With this system, only a receiver for the radar pulses is needed in the missile. The output of the receiver controls activating circuits that function when pulses of the correct amplitude and sequence are received.

The most widely used command guidance system uses a radar tracking unit and a radio command link. The missile contains an FM receiver and AF channel selectors.

7B6. Operation of a typical system

A typical command guidance system might be used to control a surface-to-surface missile fired by a ship against a fixed installation ashore. The missile, during the early part of its flight, would be tracked by radar aboard the firing vessel. Because the geographical location of the target and the firing vessel are both known, the required missile course can be accurately calculated. Information from the missile-tracking radar may be fed to a computer, or it may be plotted on a visual display, or both. When the tracking data indicates that the missile has turned from its calculated course, commands can be transmitted to turn it back.

If the target is at fairly short range, the firing vessel may control the missile throughout its entire flight. At longer ranges, the tracking and command functions may be transferred to an aircraft, or they may be transferred successively to one or more ships located nearer to the target.

C. Radar Command System

7C1. General

There is great similarity between radio and radar command guidance systems. However, there are some differences which must be considered when a guidance system is being designed.

Most radar command guidance systems depend on "sampling" control, since it is not possible to control all of the missile functions at once. Each must take its turn in the control sequence. Consequently, after a given function has received a command, there will be a time delay before the next command is received. The length of this delay will depend on the number of functions to be controlled.

When radar is used for control, the fidelity or accuracy of control is limited by the allowable variations in pulse rate or amplitude. (Excessive variations will affect the tracking accuracy.) The accuracy of control is also limited by the ability of the missile equipment to measure these variations accurately.

There are several ways in which commands can be sent by radar. For example, the pulse repetition rate (PRR) of the radar may be frequency modulated in order to turn the missile in the desired direction. If the PRR is unmodulated, no control signal is sent to the missile. If the PRR is modulated so that it increases, the missile will turn in a certain direction; if the PRR decreases, the missile will turn in the opposite direction. Since the PRR can be varied by the modulation frequency, it is possible to make the amount of turn proportional to the deviation from the normal PRR, and thus obtain accurate control.

This system requires some form of multiplexing or switching control, so that operations take place in a definite sequence. As an example, there may be five possible operations and each may be controlled by a 1/100-second signal of the proper pulse rate. A complete set of control signals could then be sent every 1/20 second.

The control pulses may be coded in sequence so that each pulse controls a particular operation. As soon as a full set of operations is covered, the sequence starts over again. The pulses may be modulated either in amplitude or by their position on a time scale.

Other methods by which the control signal may be sent to the missile via the radar tracking beam are:

1. Dual pulses are sent, and the spacing between pulses is varied according to the desired control signal. Or single pulses are transmitted, and when a particular control signal is desired, double, triple, or quadruple pulses are sent.
2. Alternate pulses may be displaced ahead of or behind their normal position and the desired control signal is determined by the amount and direction of the displacement. This is known as the displaced-pulse method of control.
3. By varying the width of the radar pulse, each control signal may be determined by the pulse width.
4. The radar pulse may be amplitude modulated so that the frequency of the modulated pulse envelope will determine the control signal.
5. The pulse rate may be varied in discrete steps, with each frequency representing a different operation, such as climb or dive, right or left, explode, or dump. The degree of any operation, such as the amount or rate of climb, may be determined by the number of repetitions of the signal or the length of time a particular signal is maintained.

The use of the tracking radar beam as a control medium results in economy of equipment, because the radio control transmitter is no longer needed.

As in any other communications equipment, the bandwidth of the modulated signal determines the amount of information that can be transmitted in a given time. A radar signal with a pulse repetition rate of two thousand cycles per second would limit the number of functions that could be controlled, as well as the rate at which the control signals could be changed. But for some missile systems this bandwith is adequate, because only a few missile functions are under control by command guidance. And, if the rate of signal change is not too great, there will be enough bandwidth to allow modulation of the radar beam with several signals simultaneously.

If there are missiles in the vicinity of the beam other than the one being tracked, there

must be some coding or frequency discrimination method used, so that each missile will respond only to its own control signals. Therefore, if there is any likelihood that the spacing between radar beams is not sufficient, each missile launched from a particular control station must have either special coding equipment or at least a special receiver adjustment to ensure response to the correct signal.

Although the useful types of modulation are limited when radar is used for missile control, the susceptibility of the system to jamming is greatly reduced by the use of the narrow beam. In this respect the radar system is slightly superior to radio control, especially when the radar pulses are sent in a coded sequence. But radio is superior for sending commands to the missile, since by using tone modulation it is possible to activate several circuits at the same time.

D. Long-Range Hyperbolic Guidance

7D1. Loran principle

Standard Loran was developed primarily for long range navigation over water. The system requires at least two transmitting stations—one a MASTER, the other a SLAVE. The stations are separated by a distance of several miles, and the geographic location of each station is accurately known.

The master station transmits a signal which is radiated in a circular pattern. When the signal reaches the slave station, or stations, it triggers the slave which then sends out a pulse that is also radiated in a circular pattern. The signals of all stations travel outward from their respective antennas as shown in figure 7D1. At any point, such as P in figure 7D1, the signals will have different times of arrival because of the distances traveled and the differences in transmitting time.

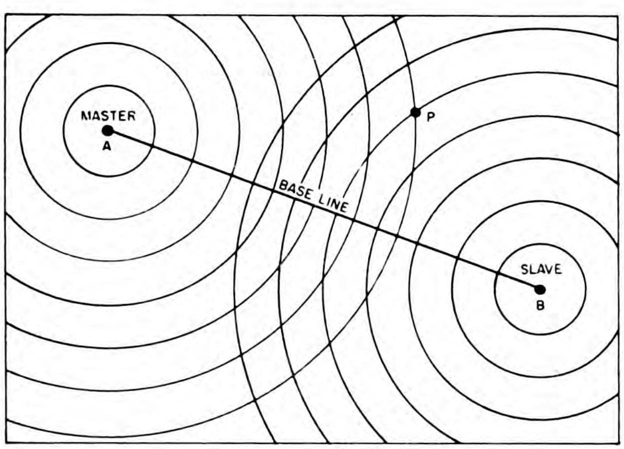

Figure 7D1.—Basic Loran system.

The difference in the range from master to P and slave to P, figure 7D1, can be determined mined by measuring the difference in time of arrival of the two signals. A set of points for which this difference is constant can be connected together to form one line of a surface called a HYPERBOLOID OF REVOLUTION. Points for different values of constant range difference can be determined and connected together. The curves that result form a family of hyperbolas as shown in figure 7D2.

Any plane passing through the line A-B, in figure 7D1, intersects these hyperboloids in such a manner that, in this plane, there passes only one branch of a hyperbola that is characterized by a constant range difference. Thus, if the range difference is known, a hyperbolic line of position on that plane is defined.

If a second line of position from another pair of Loran stations is known, a fix in the plane is determined by the intersection of the two hyperbolas.

Charts are available that show the hyperbolic lines of position associated with pairs of Loran stations in various areas. By using these charts, a navigator, knowing the range difference by radio measurement, can select his lines of position to get a fix.

Some work has been done toward the use of hyperbolic lines of position for missile command guidance. Therefore the basic parts of such a system will be briefly described.

MASTER TRANSMITTER. The master transmitter is a conventional CW transmitter radiating about 100 kw of power on one of several frequencies between 1700 and 2000 kc. The output is a series of pulses of accurately timed length. The ground wave range over sea water is about 700 nautical miles in the

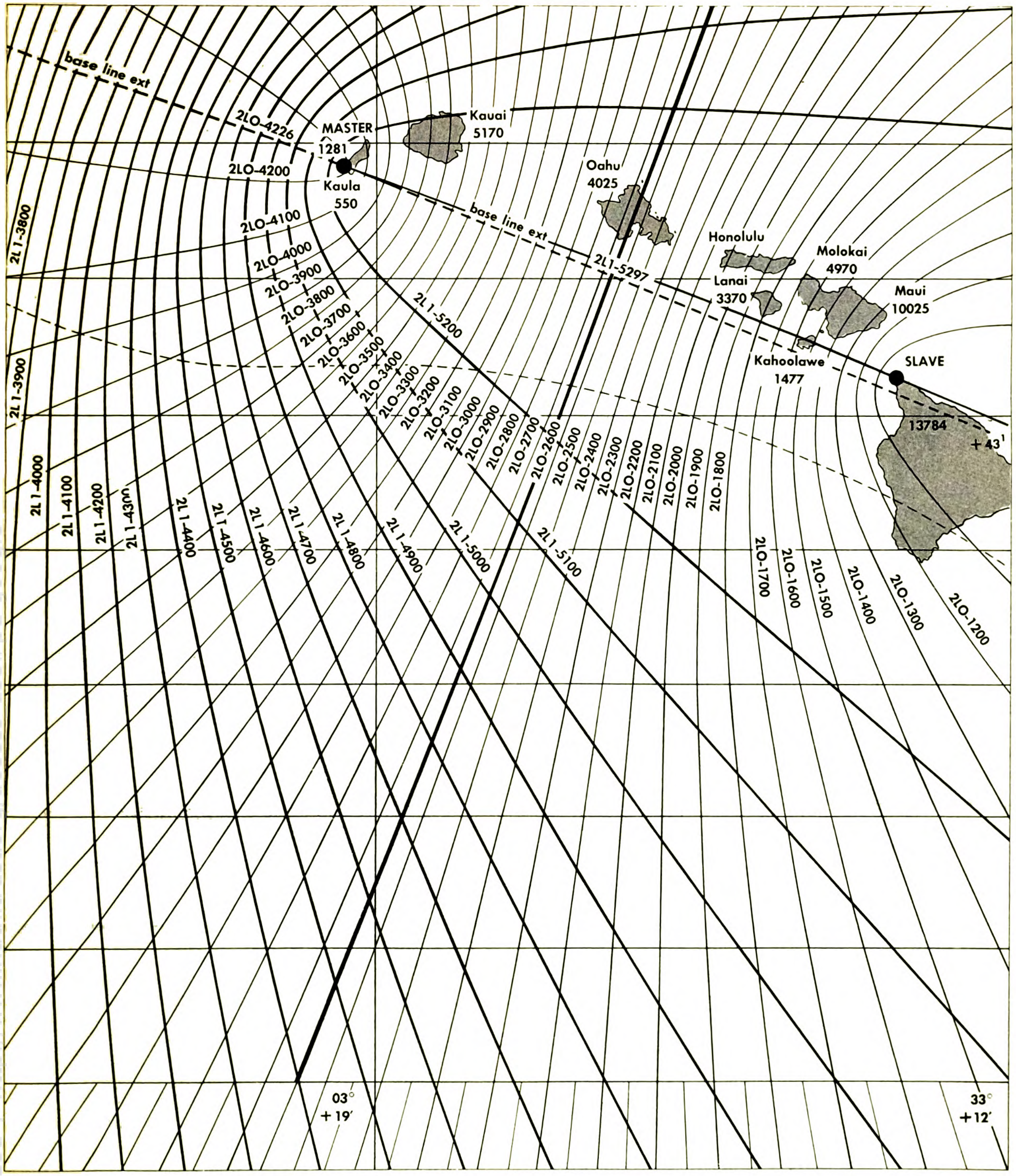

Figure 7D2.—Hyperbolic curve family.

daytime. The daytime range over land is seldom more than 250 miles even for high-flying aircraft. At night, the ground wave range over sea water is reduced to about 500 miles by the increase in atmospheric noise; but sky waves, which are almost completely absorbed by day, become effective and increase the reliable night range to about 1400 miles. The variable transmission times of the sky waves reduce the accuracy of the system. But the timing errors become smaller as the distance increases. This partially compensates for the increasing geometric errors, so that navigation by sky waves compares well with celestial navigation.

SLAVE TRANSMITTER. The slave transmitter is a duplicate of the master transmitter except that the slave station includes a receiver to pick up the transmission of the master station. A relay in the output of the receiver keys the slave transmitter, so that it sends out pulses of the same length as those sent by the master station. But there is a difference in the start and stop time of the pulses, due to the time it takes a signal to reach the slave station from the master station.

AUTOMATIC RECEIVER. The delay between the sending of the master pulse and the slave pulse ensures that the master station pulse will always be picked up first at any receiver located in the area serviced by the system. The pulse time differences can be measured by displaying the pulses on a cathode ray oscilloscope that is provided with a precisely timed sweep. A missile using this system would have to measure the time difference automatically; this requires a relatively complex receiver. Because the system has no human operator, it is not possible to read pulse time difference on a cathode ray tube. Instead, the receiver uses a phase-shifting mechanism to match the phase of the slave station signal with that of the master station signal. The amount of phase shift required to produce a phase match gives an accurate indication of the difference in range of the two stations.

SERVO LOOPS. Servo loops are used to drive the phase-matching mechanisms. Signals received from the master and the slave stations are sent to a mixer; when the two are exactly in phase, the mixer output will be at a maximum. The mixer output is used to drive the phase-shifting servos in the direction required to produce a maximum output. One servo is used to produce a phase match between the pulse envelopes of the two stations. This provides a rough measurement of pulse time difference. A second servo matches the phase of the two RF carrier signals, to provide an extremely accurate measurement. Additional servos perform the same function for the second slave-master pair.

COMPUTER AND AUTOMATIC PILOT. The two time-difference measurements, as indicated by the magnitude of the phase shifts produced by the servo mechanisms, is fed to a computer. The computer uses this information to calculate the position of the missile. Since the position of the target is known, the computer can then calculate the course which the missile must take to reach this target. The computer sends this information to the automatic pilot, which holds the missile on the required course.

When a hyperbolic system is used, a change in course is not apparent until the new course has been held for some time. In other words, the system gives an indication of position, not of direction. This is valuable since it makes missile navigation independent of air currents, and course and speed derived from hyperbolic systems are ground course and ground speed.

7D2. FM Loran system

A frequency-modulation (FM) Loran system is similar in function to the one just described, but it uses a unique approach to eliminate uncertainty. In a three-station FM system the outputs of three transmitters, master and two slaves, are frequency modulated by a sine wave. These three transmitters, with different low-frequency carriers, are frequency modulated by the same AF signal so as to obtain identical modulation in frequency and phase for the three transmitters. The time for one cycle of the modulation frequency must be long enough to allow the RF signal to get to the maximum range of the system.

A pair of transmitted signals are compared by measuring the relative delay required to produce a phase match in their modulating signals. Phase matching is indicated by an output of maximum amplitude from the mixer. As in the system previously described, the

output of the phase-shifting servos is fed to a computer, which controls the operation of an automatic pilot. The FM system appears to ensure greater accuracy and reliability, because of its higher signal-to-noise ratio. But in its present state of development, the equipment required is too bulky for convenient use in guided missiles.

E. Short-Range Hyperbolic Guidance

7E1. General

The range of any hyperbolic navigation system depends on the frequency of the radiation that is used as a carrier. Ultra-high frequencies can be used for short range guidance systems with good accuracy. However, they are not good at the longer ranges.

By using microwave frequencies, a small, highly directional antenna can be mounted on the missile without interfering with its aerodynamic characteristics. The directional characteristics of the antenna are narrow in the vertical plane and fairly wide in the horizontal plane. These directional characteristics decrease the possibility of enemy countermeasures by jamming.

It is necessary to discriminate against sky wave interference in synchronizing the ground stations. To ensure accuracy, the synchronizing pulse must be transmitted via a direct, constant path. There should be no variable factors such as SKIP EFFECT which would alter the transmission of synchronizing signals.

It is difficult to establish a condition in which these variable factors do not change the transmission characteristics of an ultrahigh frequency (UHF) system. This is especially true where the baseline between stations is longer than the line-of-sight distance. All UHF installations require a means of relaying the synchronizing signal without introducing variations or unpredictable delays.

7E2. Three-station system

The transmitting stations use precision timing signal generators to modulate RF transmitters. These transmitters use the same kind of tubes and circuitry as a radar transmitter operating in the same frequency range. They must have high power output to give a high signal-to-noise ratio near the limit of their effective range. For UHF, this is normally assumed to be line-of-sight.

Because of line-of-sight limitations, the separation between ground stations is usually limited to less than 100 miles. When one master and two slave stations are used under these conditions, the short baseline results in a very short useful range. The lines of position in such a system would cross at an obtuse angle, which would make an accurate fix difficult at points distant from the baseline. Therefore, three-station systems have been modified to overcome some of the limitations.

7E3. Four-station system

A four-station UHF system has the advantages of both line-of-sight transmissions and long baseline systems. Two pairs of stations are used; each pair consists of one master and one slave operating on the same frequency, and they are properly synchronized.

The pairs of stations are separated by enough distance so that lines of position on the hyperbolic grid are more nearly at a right angle to one another in the intended target area. If a second similar system is superimposed on the two-station grid at nearly a right angle, the missile position can be accurately determined.

To set up this system, one pair of guidance base stations is used to give the bearing guidance hyperbola. One time-difference line of this pair is chosen so that it will cross the target area of the missile. It then serves as the desired track for the missile. The guidance system in the missile determines when the received signal pulses have the proper TIME SEPARATION to show ON COURSE. If the received signals do not have the desired time difference, the guidance equipment can determine whether the missile is right or left of the desired course. The error signal from the guidance section is sent to the control section which makes the corrections to bring the missile on course.

The second pair of guidance base stations is used to determine the range. A particular time-difference line of this system is calculated

to pass through the correct point for starting the terminal phase of the flight. The intersection of this RANGE LINE and the COURSE LINE gives a fix at the pre-dump point. To do this, the missile guidance equipment develops a voltage (from the base guidance signal) that is proportional to the distance from the preselected target location. This varying output voltage approaches zero at a rate which is proportional to the velocity of the missile.

This output voltage is converted to another voltage which is proportional to the rate of change of the output voltage. This proportional voltage is then a measure of the missile ground speed. It is necessary to compensate for expansion of the hyperbolas as the distance from the transmitter increases. The determination of ground speed is necessary so that the missile does not overshoot or undershoot the target due to a change in air speed from the expected value.

It should be kept in mind that command guidance systems are in a state of constant development, and that future systems may differ considerably from those described here.

CHAPTER 8
BEAM-RIDER GUIDANCE

A. Introduction

8A1. General

The previous chapter discussed various methods by which commands can be sent from a control point to a missile, to control the missile flight from launching point to target. Beam-rider guidance system is in some respects similar to command guidance. In both systems, target information is collected and analyzed by suitable devices at the launching site or other control point—rather than by devices within the missile. In both systems, the missile makes use of guidance signals transmitted from the control point.

But beam riding is not considered a form of command guidance. The principal difference is this: in a command system, guidance signals are specific commands, such as "steer right," or "steer left." But the transmitter of a beam-rider guidance system transmits only information, not commands. By projecting a narrow beam of radar energy, the transmitter at the control station indicates the direction of the target (or, in some systems, the direction of a calculated point of intercept). The guidance system within the missile must interpret the information contained in the radar beam, and then formulate its own steering commands. These commands operate to keep the missile as nearly as possible in the center of the beam. The missile can thus be said to "ride" the beam to its target.

The beam-rider system is highly effective for use with short-range and medium-range surface-to-air and air-to-air missiles. For missiles of longer range, a beam-riding system may be used during the midcourse phase of flight, while the missile is still within effective range of the beam-transmitting radar. As it approaches the limit of beam-riding range, the missile may switch over to some other form of guidance.

8A2. Application to U.S. Navy missiles

The development of missile guidance systems with minimum susceptibility to enemy countermeasures, and with maximum probability of hitting the target, is the primary objective of the U. S. Navy missile program. The program is continuous and has a high priority rating. Two missiles, Terrior and Talos, developed under this program have been operational for some time. Both of these are surface-to-air missiles using beam-rider guidance. This chapter will give information of a general nature on guidance systems that might be used with missiles of this type. It should be kept in mind that security requirements prevent a detailed description of the guidance system of any specific missile.

B. Guidance Antennas

8B1. General

The radar energy that forms the guidance beam is transmitted by an antenna at the control point. Radiated energy tends to spread out equally in all directions. But by mounting a suitable reflector behind the antenna, a large part of the radiated energy can be formed into a relatively narrow beam. A narrow beam can point out the target direction with sufficient accuracy for the missile to score a hit, and concentration of the radiated energy into a beam extends the effective range of the system.

Figure 8B1 compares the radiation from a radio antenna with that from a lamp. Both light waves and radio waves are electromagnetic radiation; the two are believed to be identical, except in frequency of vibration. From both sources, energy spreads out in the form of spherical waves. Unless they meet some obstruction, these waves will travel outward indefinitely at the speed of light. Because of its much higher frequency, light has a much shorter wavelength than radio waves. This is suggested in figure 8B1, but it cannot be shown accurately to scale. The wavelength of radar transmission may be measured in

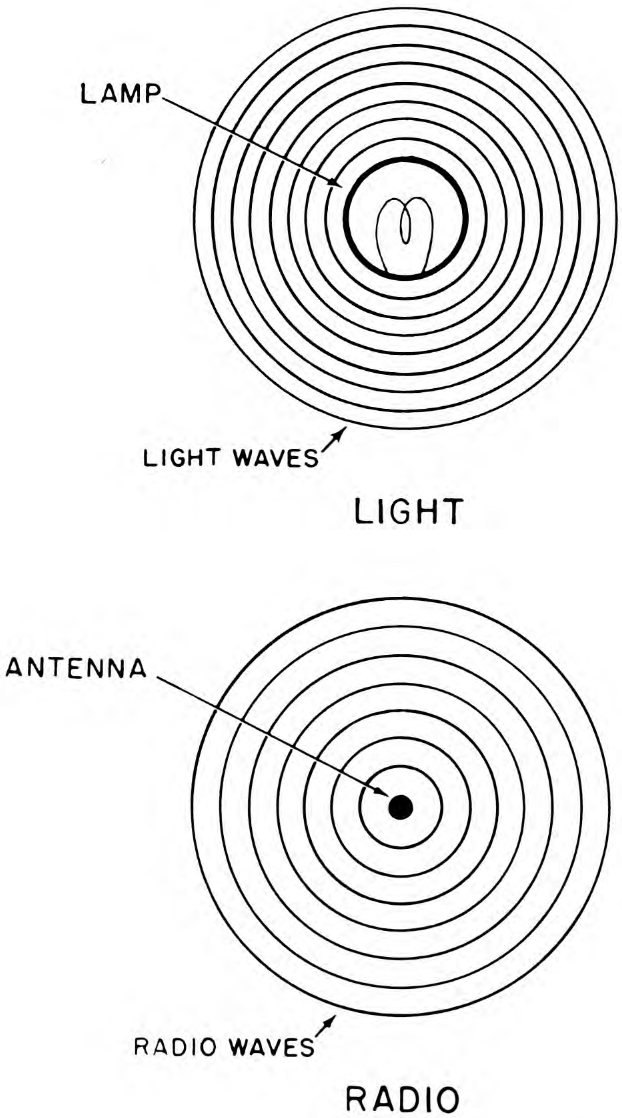

Figure 8B1.—Comparison of radiation from a lamp and a radio antenna.

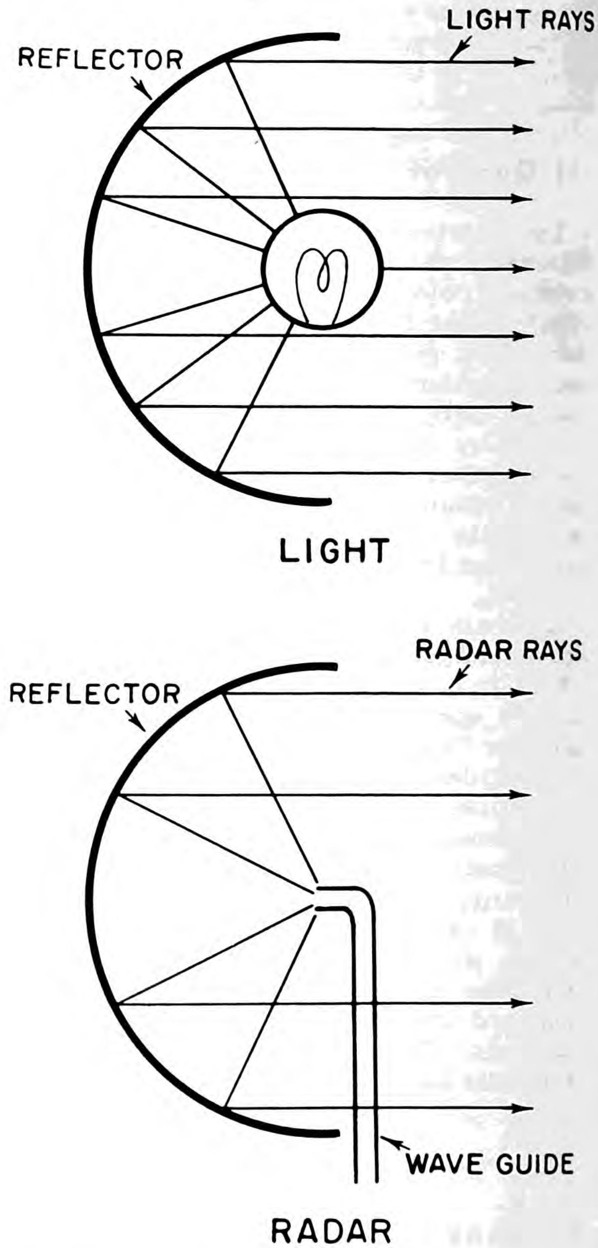

Figure 8B2.—Use of reflectors to form beams of radiant energy.

centimeters; the wavelength of light ranges from about three to seven ten-thousandths of a millimeter.

You are, of course, familiar with the use of polished reflectors to form beams of light. An automobile headlight is an example of this, although it produces a fairly wide beam. A spotlight produces a more narrow beam. The upper part of figure 8B2 represents the reflection of light by an "ideal" reflector. The emerging rays are parallel; the beam is no wider than the reflector itself, and it does not diverge. But an ideal reflector is hard to achieve in practice. It must be a paraboloid of revolution—that is, the surface generated by a parabola rotated on its axis. It must be highly polished; its surface irregularities must be small compared with the wavelength of light. And the light source must be a single point, located at the focus of the paraboloid.

The lower part of figure 8B2 represents the reflection of radar waves. Again, the surface

of the reflector is a paraboloid. But it need not be highly polished, because of the longer wavelength of radar. The source of radiation is the end of a waveguide. Unfortunately, this is not a point source; it must have a finite area.

It should be noted that a light RAY is simply a convention used in diagrams of optical instruments. Such rays do not exist in nature. They are imaginary lines that indicate the direction in which the wavefronts are moving. Although RADAR RAYS are not a familiar convention, they are used in figure 8B2 to show the direction in which the radar waves are moving.

Of course the lamp shown in figure 8B2 is radiating light in all directions. The light from the front surface, which does not strike the reflector, will be scattered widely. In some spotlights, the front surface of the lamp is shielded, so that the only rays that leave the spotlight are those that have been reflected. Such a spotlight produces a sharply defined beam, with little or no scattered light. The same effect is achieved in radar by directing the opening of the waveguide backward, toward the reflector.

But no radar can produce an ideal beam of parallel "rays." For one thing, the end of the waveguide is large, compared to the ideal point source. For another, a reflector of practical size is not sufficiently large compared with the wavelength of the radiated energy. A radar beam therefore diverges and forms a lobe, like the one in figure 8B3. The student should clearly understand that such a lobe is merely a convenient way of representing the beam on paper; it is in no sense a "picture" of the beam. Some of the radiated energy will be scattered outside the lobe. And the radiation does not end abruptly at a certain distance from the transmitter, as the diagram implies. The lobe, if it can be pictured in three dimensions, can be thought of as a surface, all parts of which receive an equal amount of energy. This can be considered the minimum energy that is useful for our purpose (missile guidance or target tracking). And the lobe in figure 8B3 is not drawn to scale. The diameter of the reflector is in the order of two feet; the length of the lobe may be from 20 to 50 miles. Its useful width may be four or five degrees. At any given distance from the transmitter, the signal is strongest along the axis of the lobe.

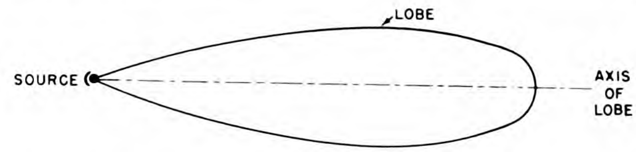

Figure 8B3.—How r-f energy is concentrated in a lobe.

8B2. Conical scanning

In a beam-rider guidance system, radar must accomplish two things; it must track the target, and it must guide the missile. It would be difficult to do either of these things with a simple lobe like the one in figure 8B3. For example, assume that a target is somewhere on the lobe axis, and that the receiver is detecting signals reflected from the target. If these reflected signals decrease in strength, it will be apparent that the target has flown off the axis, and that the beam must be moved to continue tracking. The beam might be moved by an operator who is tracking the target with an optical sight; but such tracking would be slow and inaccurate, and would be limited by conditions of visibility. An automatic tracking system requires that the beam SCAN, or search, the target area.

Again, assume that a missile is riding the axis of a simple beam. The strength of the signals it receives will gradually decrease as its distance from the transmitter increases. If the signal strength decreases suddenly, the missile will know that it is no longer on the axis of the lobe. But it will NOT know which way to turn to get back on the axis. A simple beam does not contain enough information for missile guidance.

By a suitable movement of either the waveguide or the antenna it is possible to generate a conical scan pattern, as shown in figure 8B4. The axis of the radar lobe is made to sweep out a cone in space; the apex of this cone is, of course, at the transmitter. At any given distance from the transmitter, the path of the lobe axis is a circle. Within the useful range of the beam, the inner edge of the lobe at all times overlaps the axis of scan.

Now assume that we use a conically scanned beam for target tracking. If the target is on the scan axis, the strength of the reflected signals will remain constant (or change gradually as the range changes). But if the target is slightly off the axis, the amplitude of the

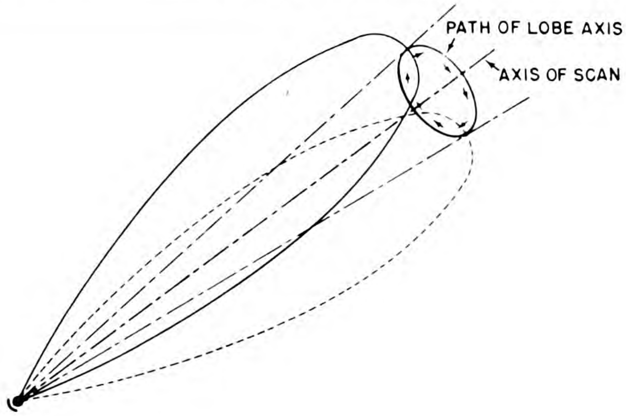

Figure 8B4.—Conical scanning pattern.

reflected signals will change rapidly and periodically. For example, if the target is ABOVE the scan axis, the reflected signals will be of maximum strength as the lobe sweeps through the highest part of its cone; they will quickly decrease to a minimum as the lobe sweeps through the lowest part. Information on the instantaneous position of the beam relative to the scan axis, and on the strength of the reflected signals, can be fed to a computer. If the target moves off the scan axis, the computer will instantly determine the direction and amount of antenna movement required to continue tracking. The computer output can be used to control servo mechanisms that move the antenna, so that the target will be tracked accurately and automatically.

When a conically scanned radar beam is used for missile guidance, the desired path of the missile is not along the axis of the beam, but along the axis of scan. Later in this chapter, we will show how the missile is able to guide itself along this axis.

C. Principles of Beam-Rider Guidance

8C1. General

Two types of beam-rider system are possible. In the simplest type, a single radar is used for both target tracking and missile guidance. In the other, one radar is used for tracking, while another generates the guidance beam. We will discuss the one-radar system, then point out briefly how the two-radar system differs.

8C2. One-radar system

In a one-radar system, the guidance beam is always pointed directly at the target, since the same beam is used for tracking. Two or more missiles can be in flight at the same time (toward the same target). The traffic handling capacity of the system is limited only by mutual interference between missiles in the beam. Once a missile has entered the beam path, no further operations are necessary at the launching site, except to maintain target tracking.

One factor must always be considered when an offensive weapon is used. That is, the enemy will always try to find countermeasures that will enable him to offset, or completely nullify, the effectiveness of the weapon. Some attempted countermeasures are fairly easy to overcome; others may be highly effective.

Since radar is used as a guidance control, the system is subject to any form of countermeasure that will interfere with the radar beam. The interference may take the form of small sheets of metal foil, called "window," dropped by the target to give false information to the tracking radar. The radar might, under some conditions, be led to track the foil sheets rather than the target.

Another form of countermeasure might be an enemy radar set working on the same frequency as the guidance radar. This type of interference is called "jamming." The nature of the beam-rider guidance system gives good anti-jamming characteristics because the beam is narrow and directional. The missile carries its receiving antennas on its after end—often on its rear airfoils. These antennas are also directional; they are most sensitive to signals originating behind the missile, and relatively insensitive to signals originating in front. To effectively jam the guidance beam, the jamming transmitter must get behind the missile. Thus a jamming transmitter would be of little value as a defensive measure for a target aircraft, because once the target gets behind a given missile, it has already successfully evaded that missile.

It is also possible to transmit the guidance beam as a series of pulses having a definite,

coded sequence and amplitude. The missile can be set to accept guidance signals only if they follow the proper coded sequence, and to reject all other signals. By using a variety of code sequences, and by changing them often, it is possible to make successful jamming very unlikely.

Beam-rider guidance is used by both air-to-air and surface-to-air missiles. In neither application is the missile actually in the guidance beam at the instant of launching, and the problem of getting it there must be solved. For air-launched missiles, this is relatively easy; the missiles are carried beneath the wings of the aircraft, fairly close to the guidance radar. And they are fired directly forward; in most situations this is toward the target, and thus parallel to the guidance beam.

But when a surface-to-air missile is launched from the deck of a ship, the "capture" problem is more complex. The missile may be trained at almost any angle (except into the ship's structure). Because the blast of hot gases from the missile booster is deflected along the deck at the time of launching, a large area around the launcher must be kept clear. The guidance radar must therefore be located at some distance from the launcher. The missile cannot be launched directly toward the target, on a course parallel with the guidance beam. Instead, it must be launched in such a direction that it will CROSS the guidance beam a few seconds after launching. It will then turn toward the target, after it has been captured by the beam.

But because the guidance beam is narrow, merely aiming the missile to cross it is not enough to ensure capture. To make capture more certain, a broad CAPTURE BEAM (fig. 8C1) is superimposed on the narrow guidance beam. Because the energy in the capture beam is spread out over a large area, its effective range is short.

During the launching phase of missile flight, the control surfaces are locked and the guidance system is inoperative. The booster propels the missile in a direction calculated to place it within the capture beam. When the booster drops away, the control surfaces are unlocked and the guidance system takes over. The missile receiver is tuned to respond to the capture beam, and to seek its axis. In so doing, it turns itself toward the target and aligns itself in the guidance beam, which has

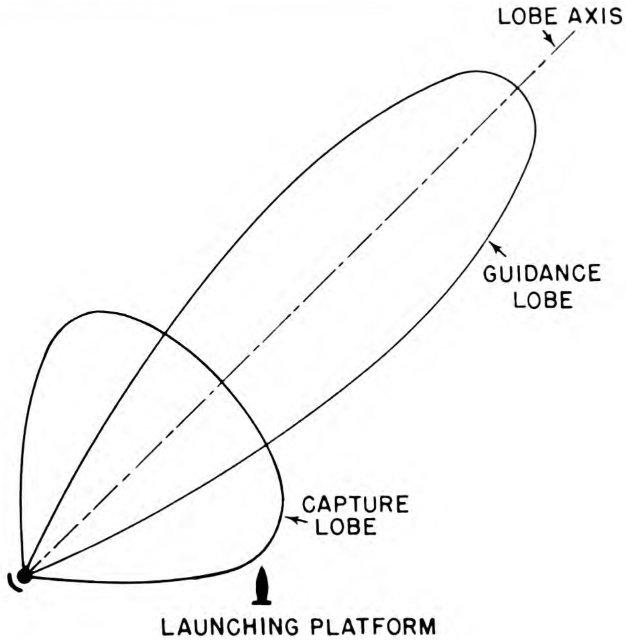

Figure 8C1.—Capture beam and guidance beam.

the same scan axis as the capture beam. After a preset interval, a timing device within the missile changes the receiver tuning. The missile will then reject signals from the capture beam, and respond only to those in the guidance beam, which has a different carrier frequency.

The single-radar beam-rider system, because it uses only one radar instead of two, has the advantage of simplicity. But the use of a single radar results in a serious problem. Remember that the guidance beam is also the tracking beam, and must therefore be pointed at the target throughout the missile flight. Except in one special case—when the target is flying directly toward the transmitter—the radar must be trained in order to follow the target. For a nearby, high-speed, crossing target, the angular rate of train will be high. The missile course, therefore, cannot be a straight line. The missile must constantly move sideways in order to stay in the beam. While the missile is relatively close to the transmitter, its lateral rate is small. But, as the missile approaches the target, the same angular rate of train will require increasing lateral acceleration of the missile.

Figure 8C2 illustrates this problem by showing three successive positions of the target and the missile. In this example, the beam

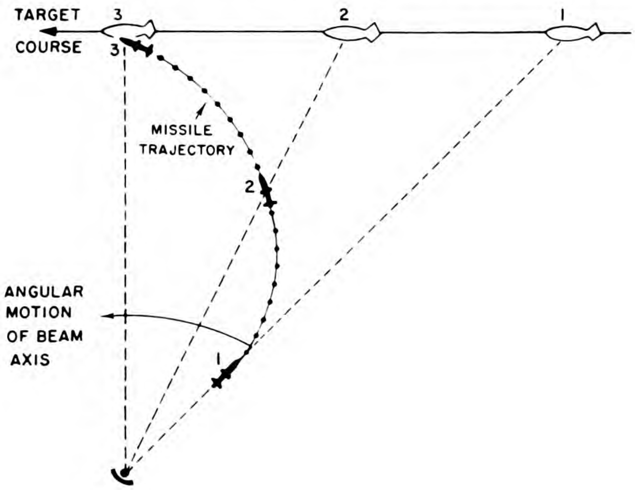

Figure 8C2.—Lateral movement of missile.

is trained to the left at an almost uniform rate. The missile, in order to stay in the beam, must accelerate to the left at a rapidly increasing rate. In the extreme case shown in the figure, the missile as it nears the target, must follow a path almost at a right angle to the beam. Even with its control surfaces in their extreme positions, the missile would probably be unable to turn at the required rate. Thus a one-radar beam rider might be useful against approaching targets, but ineffective against high-speed crossing targets.

8C3. Two-radar system

The two-radar beam-riding system uses one radar to track the target and a second radar to guide the missile. A computer is used between the two, and the guidance radar is controlled by the computer. The computing system uses information from the tracking radar to determine the trajectory necessary to ensure a collision between the missile and the target. Because the same radar beam is no longer used for both tracking and guidance, the missile need not follow a line-of-sight path, as was the case with a one-radar system.

The same countermeasures which would affect a one-radar system could be used against the two-radar system. But it would be more difficult to destroy control effectiveness, because of the two radar beams and the computer action. The computer stores guidance information as it determines the trajectory the missile is to follow. Therefore even if the tracking beam were interrupted by countermeasures for a short time, the computer would still be able to maintain the guidance beam, and hold the missile on a probable collision course with the target.

The two-radar beam-guidance system is more complex insofar as ground equipment is concerned, because of the addition of a computer and a second radar. The equipment in the missile is the same for either system.

From the information that has been given, it may be seen that the computer is an important part of a two-radar guidance system. The computer takes information—speed, range, and course—from the tracking radar. From this information, it computes the course that must be followed by the missile. Since the computer receives information constantly, it can and does alter the missile course as necessary to offset evasive action or changes in course by the target. The output of the computer controls the direction of the guidance radar antenna. Required course changes are instantly transmitted to the missile by pointing the guidance beam toward the new point of intercept.

As we mentioned earlier, lateral acceleration presents a serious problem when a one-radar guidance system is used, because the missile course is changed by the angular movement of the tracking beam. This problem is not present in a two-radar guidance system because the missile course is directed toward a collision point, rather than toward the constantly changing position of the target. Because course information is continuously fed to the missile guidance radar, the missile trajectory is straight or only slightly curved from the launching point to the target.

D. System Components

8D1. General

There are several important components, other than the missile and radar, in a complete guided missile system. As explained earlier in this text, a major part of the equipment is at the launching site. We will describe individual components that might be found in a

complete system. Keep in mind that the number and type of components will vary with individual systems, and that a mobile setup will differ from a fixed, permanent launching site.

8D2. Launching station components

The target is usually picked up at long range by a search radar. When the target is identified, the tracking radar takes over the job of following it, and determines its direction, speed, and range. This information is converted rapidly into useable form by the computer.

Because the computer is given the course, speed, bearing, elevation, and instantaneous range of the target, it can calculate the position of the target at any future time, assuming that it does not change course or speed. The computer is also given the average speed of the missile. With this information, it is able to determine the direction in which the missile must be launched to intercept the target. It is unlikely that a missile will be fired as soon as the tracking radar acquires the target. The target range is constantly changing, and the target may change course or speed as well. The computer must therefore produce a continuous solution to a continuously changing problem. At any given instant, the computer output provides the correct solution to the problem as it exists at that instant.

In a two-radar system, the computer continues to calculate the missile course after the missile has been launched, and until the target has been destroyed. Through servo mechanisms, it turns the control radar in the proper direction. In a one-radar system, the computer output is used to train and elevate the missile launchers in such a direction that the missile will enter the capture beam at the optimum angle. (If this angle is too large, the missile must make a sharp turn to get into the control beam. If it is too small, there is some danger that the missile will evade the capture beam and go out of control.)

8D3. Missile components

The receiving antenna in the missile is a very important part of its electronic installation. Through it must come all guidance signals from the control radar. There are several difficulties in determining the optimum location of an antenna on a missile. First, the antenna must not interfere with the aerodynamic stability of the missile. Second, it must be located at a point where it will not be damaged by the rapid acceleration as the missile is launched, and where wind will not tear it loose. Finally, the antenna must be located where it can effectively pick up the signals of the guidance beam. The antenna location that has been found most satisfactory is on the missile tail surfaces.

The missile antenna is highly directional, and most sensitive to signals received from behind the missile. The roll-control system of the missile keeps it stabilized so that the antenna polarization remains constant.

The guidance signals picked up by the missile antenna are fed to a receiver. After the signals are amplified and demodulated by the receiver, they are fed to a computer. If the missile is off the scan axis of the guidance beam, the computer will determine both the direction and the magnitude of the error. It will then give the control system the commands required to bring the missile back onto the scan axis.

E. System Operation

8E1. General

Earlier sections of this chapter have shown that a number of components are required to complete a beam guidance system. Each component must function properly if the missile is to destroy the target. But no system can be expected to operate beyond its natural limitations.

One of the factors limiting the effective range of radar is the curvature of the earth. The effective range of a radar beam can be expressed in terms of transmitting and receiving antenna heights above the earth's surface. The formula is

$$R_E = \sqrt{2H_t} + \sqrt{2H_r}$$

where H_t and H_r are the heights of the transmitter and receiver antennas in feet, and R_E is the effective range in miles.

It can be seen that raising the height of either antenna will increase the effective range. Thus it appears that a missile, because of the altitude at which it travels, can be controlled at extremely long range. But this is not true. The transmitter power necessary to deliver a satisfactory control signal increases rapidly with distance. Therefore, for long range missiles, a single beam-rider guidance system would be unsatisfactory. But these limitations can be overcome by using beam-rider guidance during the first part of the missile flight, then switching to a different guidance system before the missile flies beyond control of the radar beam.

8E2. Tracking radar

We have mentioned that the tracking radar furnishes information as to the position of the target. All target position references are made with respect to the scan axis of the tracking lobe.

The amount of energy in the beam falls off rapidly at points away from the center of the lobe. Figure 8E1 shows the relative amounts of energy transmitted at various angles to one side of the lobe axis. Because of the variation in transmitted energy, there will be a corresponding variation in the strength of signals reflected by targets at various angular distances from the center of the lobe.

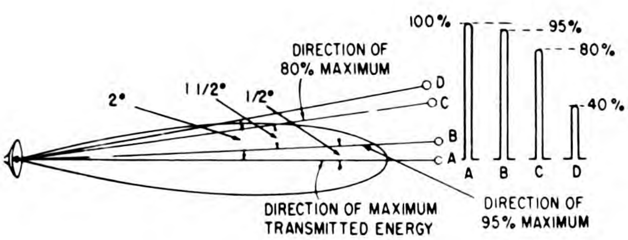

Figure 8E1.–Radiated energy variation.

As we mentioned earlier, the tracking system is automatic. After the tracking radar has acquired the target, tracking is maintained without the help of a human operator. But the action of the tracking system is monitored by an observer, who may take over and track the target manually if the automatic system fails.

At the monitor station, indications of target position relative to the scan axis of the tracking beam are presented on two cathode-ray tubes (CRT's). Figure 8E2 shows how the vertical position of the target, relative to the scan axis, is presented on a CRT. In the upper part of the figure, the target is on the scan axis. Remember that the tracking lobe is scanning a conical pattern in space. The lobe is shown in the highest and the lowest positions of its scan pattern. For each of these two positions, the CRT produces a pip, the height of which is proportional to the strength of the reflected signal. Since the two pips are of equal height, they indicate that the reflected signals are of equal strength when the lobe is in its highest and lowest positions. This can occur only when the target is vertically centered with respect to the two lobes--that is, in a transverse plane through the axis of scan.

The lower diagram shows the effect of a target above the scan axis of the beam. When the lobe is in its highest position, the target is directly on the lobe axis, and the height of the CRT pip is a maximum. When the lobe is in its lowest position the target is far off the lobe axis; its reflected signal will be much weaker, and the pip on the CRT correspondingly small. This indicates that the target is above the scan axis.

A second CRT indicates the relative strength of the reflected signals when the lobe is at its extreme left and extreme right positions. In an emergency, the operator can track the target manually by moving the radar so as to keep the pairs of pips of equal height on both CRT's.

8E3. Control radar

A block diagram showing the sections of a beam-rider guidance system is shown in figure 8E3. The guidance beam pattern is formed by the antenna of the guidance radar. Transmitter sections are shown in the dashed squares of figure 8E3. The sections in solid lines are in the missile.

As explained earlier, a conical scan is one in which the lobe axis of the radar beam is moved so as to generate a cone. The vertex of this cone is at the antenna. It is possible to produce a conical scan by any of several methods.

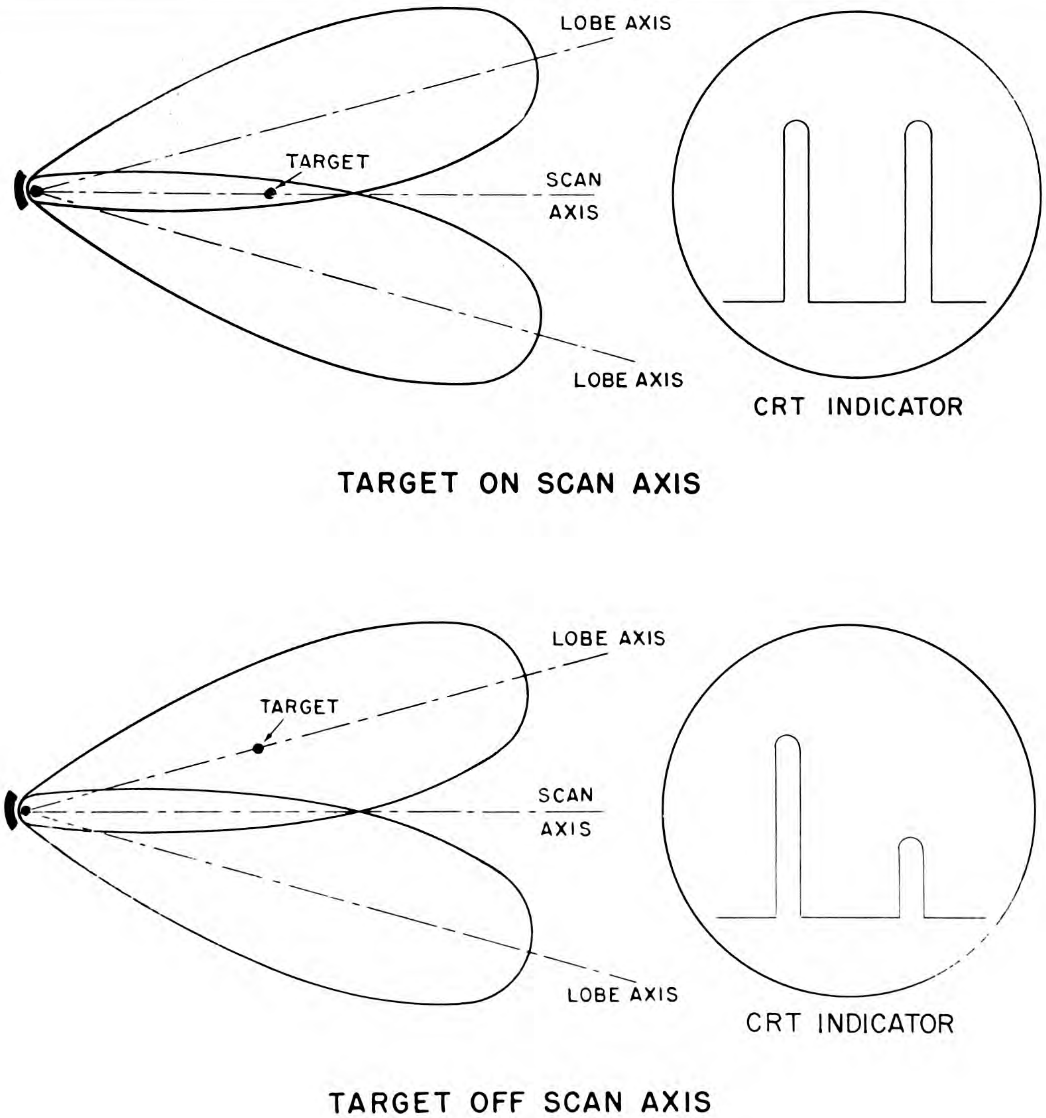

Figure 8E2.—How CRT indicates target position in relation to the scan axis.

ROTATING DIPOLE. A dipole antenna consists of two wires or rods mounted end-to-end. R-f energy is fed into the center of the antenna, with the two poles receiving signals of opposite phase. The overall length of the antenna is half a wavelength.

The proper length for a dipole IN FREE SPACE can be determined from the formula:

$$\text{Length (feet)} = \frac{492}{\text{Frequency (msc)}}$$

However, free space conditions do not exist in actual antenna installations, and the most efficient length for a half-wave antenna is usually about 95 percent of that given by the formula.

The formula shows that a dipole antenna for 450 mcs would be about 13 inches long. Therefore, the physical size of a highly directional array (antenna and reflector) for that frequency would be small enough for easy mounting and rotation.

When we speak of rotating a dipole, we do not mean that the antenna is turned or rotated about its center. If this were done, the antenna polarization would change as the antenna turned. Polarization would be vertical when

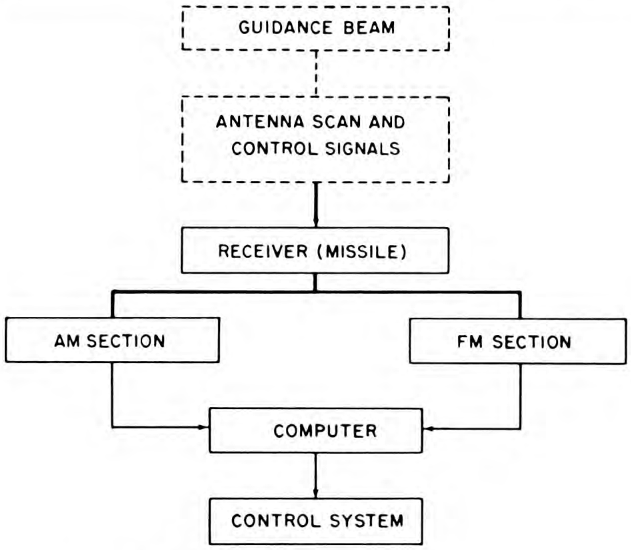

Figure 8E3.—Block diagram of beam-rider system.

the antenna was perpendicular to the ground, and horizontal when the antenna was parallel to the ground. Should this condition exist, control of the missile would be erratic because the anti-roll controls on the missile are designed to maintain constant polarization of the missile antenna.

Figure 8E4 shows how the dipole may be rotated without changing its polarization. In this diagram, you're looking into the concave face of a paraboloid reflector. The antenna is mounted in a plane that passes through the focal point at a right angle to the reflector axis. As the antenna rotates it stays in this plane, and continues to point in the same direction; its center describes a circle around the focal point.

ROTATING REFLECTOR. When the antenna rotates, as described above, the relative motion between antenna and reflector produces a conically scanned beam. It is apparent that the same relative motion can be produced by using a stationary antenna and rotating the reflector about a point off its axis.

NUTATING WAVEGUIDE. A waveguide is a metal pipe, usually rectangular in cross-section, which is used to conduct the r-f energy from the transmitter to the antenna. The open end of the waveguide faces the concave side of the reflector, and the r-f energy it emits is bounced from the reflector surface.

A conical scan can be generated by nutation of the waveguide. In this process, the axis of the waveguide itself is moved through a small conical pattern. Figure 8E5 is an attempt to represent this three-dimensional movement in a two-dimensional diagram. Nutation is difficult to describe in words, but easy to

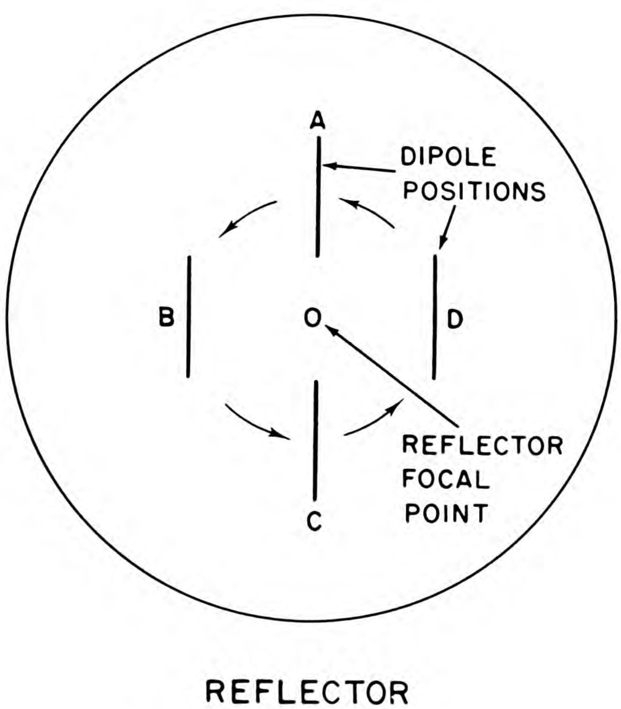

Figure 8E4.—How a dipole is rotated.

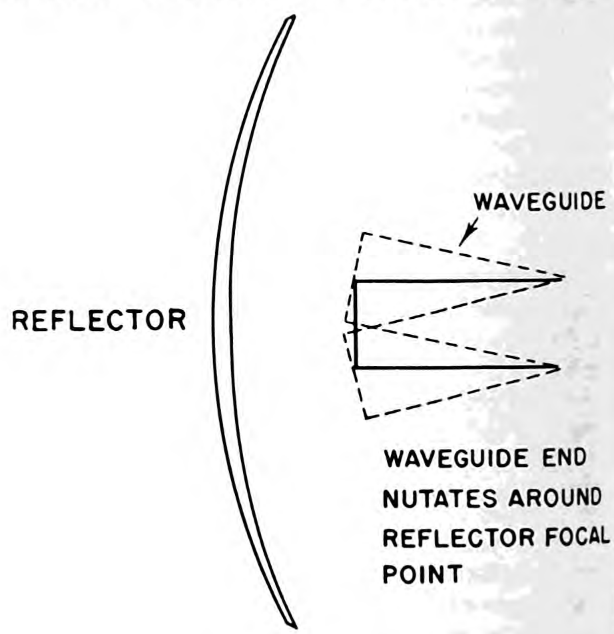

Figure 8E5.—Nutation of the waveguide.

demonstrate. Hold a pencil in two hands; while holding the eraser end as still as possible, swing the point through a circle. This motion of the pencil is nutation. (The pencil point corresponds to the open, or transmitting, end of the waveguide.) In an actual installation, this movement of the waveguide is fast, and of small amplitude. To an observer, the waveguide appears merely to be vibrating slightly.

8E4. Missile response

A beam-riding missile must guide itself to the target by following the scan axis of its guidance beam. The only guidance information available to the missile is that contained in the beam. From this information, the missile guidance system must determine three things: (1) whether or not the missile is on the beam axis; (2) if not, how far it is off the axis, and (3) which way to go to get back on the axis. The first and third requirements are fairly obvious. The necessity for measuring the AMOUNT of error is less apparent.

During the early stages of guided missile development, one of the more serious problems was "overshooting." When a missile moved off course, and received a signal intended to correct the error, it would turn back toward the course, but overshoot and go too far in the opposite direction. This effect was caused by the lag in the response of the control system to guidance signals, and in the response of the missile itself to movement of its control surfaces. For practical purposes, this problem has been solved by the use of error signals proportional in magnitude to the errors they are intended to correct. Thus if a missile is far from the beam axis it will generate a large error signal, and its control surfaces will be turned through a relatively large angle. But, as the missile moves back toward the beam axis, its error signal steadily decreases, and the angle of its control surfaces is decreased accordingly. At the instant the missile reaches the beam axis, its control surfaces will (in theory at least) have reached their neutral position, and overshooting will be prevented.

Now let us see how the missile determines whether or not it is on the scan axis. Figure 8E6 represents a missile below the scan axis of the guidance beam. The path of the lobe axis is a circle. And the amplitude of the

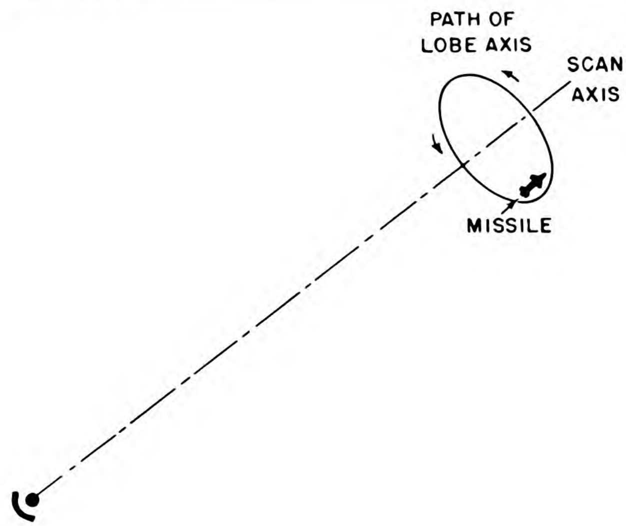

Figure 8E6.—Missile below the beam axis.

radar signal is at a maximum along the axis of the lobe. As the lobe axis sweeps near the missile, the signal will be strong; as it sweeps away from the missile, the signal will decrease. To the missile, it will appear that the signal strength is regularly changing in amplitude, at the same frequency as that of the scan cycle.

The missile receiver is provided with a detector, which eliminates the r-f carrier frequency and produces a sine wave signal of the scan frequency. When this a-m signal is present, the missile knows that it is OFF the scan axis of the beam. When the a-m signal is absent, the missile knows that it is ON the axis. To see this clearly, look at figure 8E6 and imagine the missile on the scan axis. It is now at the same distance from the lobe axis throughout the scan cycle, and the amplitude of the r-f signal it receives remains constant.

From the AMPLITUDE of the a-m signal, the missile can determine how far it is from the scan axis. When the missile is on the axis, the amplitude of the a-m signal is zero, indicating zero error. If it is only a short distance from the scan axis, its distance from the lobe axis changes only slightly during the scan cycle. The a-m signal will thus be small, indicating a small error. Now, looking at figure 8E6, imagine the missile at some point on the circular path of the lobe axis. The variation in its distance from the lobe axis during the scan cycle is now at a maximum. The a-m signal will also be at a maximum,

producing the maximum error signal and maximum movement of the control surfaces.

(It is apparent that if the missile moves to a point OUTSIDE the circular path of the lobe axis, the error signal will decrease. But this does not happen in practice, unless the missile is defective. The guidance and control systems are too sensitive to allow so large an error to develop.)

How the missile determines the DIRECTION of its error can best be explained in two steps. Figure 8E7 shows an imaginary scanning system in which the lobe of radar energy, instead of sweeping out a cone, has only two positions—up or down. The two lobes are transmitted alternately. The figure shows the missile below the scan axis, near the axis of the lower lobe. The missile will receive signals from both lobes, but those from the lower lobe will be of greater amplitude. If we can provide the missile with some means for distinguishing between the two lobes, so that it can tell WHICH ONE has the stronger signal, it can determine the direction of its error. For example, if the missile in figure 8E7 can determine that it is the LOWER lobe that has the stronger signal, it will know that it must move up to get back on the scan axis.

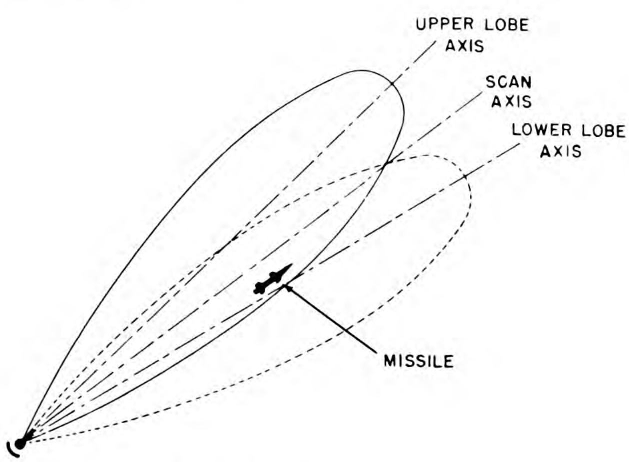

Figure 8E7.—Two-lobe scanning system.

There are two fairly simple ways in which we can identify the two lobes so that the missile can distinguish between them. (We cannot, of course, make them of different amplitude, since a missile on the scan axis would then detect a false error signal.) Beam-rider radar transmission consists of an extremely high-frequency carrier wave, which is transmitted in short bursts, or pulses, separated by periods of no transmission. The pulse repetition rate is ordinarily in the order of from one to a few thousand per second. We can identify the two lobes shown in figure 8E7 by making them differ either in carrier frequency or in pulse repetition frequency. In either case the missile could easily be provided with a means for distinguishing between them, and could then determine the direction of its error.

Thus the imaginary two-lobe scanning system could be used for guiding a beam rider in a vertical plane. If we add two additional lobes, each of which the missile can distinguish from the other two, it would also be possible to guide the missile to right or left. It should now be apparent that we can guide the missile in any direction by using a conical scan.

Look back at figure 8E6. Assume that we vary the signal frequency (either the carrier or the pulse rate) sinusoidally at the scan frequency. Assume that when the lobe is at its highest point, the signal frequency is at a maximum. As it moves around to the right side of its circular path, the signal frequency decreases to its average value. At the lowest position of the lobe, the signal frequency is at a minimum. It increases to average value as the lobe approaches the left side of its path, and to a maximum as it returns to its highest position. Thus the signal of the guidance beam is frequency modulated at the scan frequency. Note that the f-m signal is always present at the missile, regardless of whether it is on or off the scan axis.

The missile receiver is provided with an f-m section, the output of which is a sine wave that indicates the instantaneous position of the lobe in its scan cycle. The sine wave will have a maximum positive value when the signal frequency is maximum; it will pass through zero as the signal passes through its average frequency; it will reach its maximum negative value when the signal frequency is at a minimum.

The missile can determine the direction of its error by comparing the phase of the f-m signal with that of the a-m signal. Refer to figure 8E6 again; here the missile is directly below the scan axis. The signal will be strongest, and the a-m signal will reach its maximum positive value, as the lobe passes through its

lowest point. At that time the signal frequency will be minimum, and the f-m signal will be at its maximum negative value. Thus the two signals are 180° out of phase. If the missile were above the scan axis, the a-m signal would be strongest at the instant when the f-m signal reached its highest frequency. Both signals would be at their maximum positive value, and therefore exactly in phase. There is a definite phase relationship for every off-axis position of the missile. If the missile is directly to the right of the axis, the f-m signal leads the a-m signal by 90°; if it is directly to the left, the f-m signal lags 90° behind the a-m, etc.

Phase comparison is a fairly easy job for an electronic computer. The computer has been programmed to measure the phase relationship, to determine the direction in which the missile must move to return to the scan axis, and to send the necessary orders to the control system. The control system, in turn, moves the control surfaces to change the missile course in the required direction.

To summarize: The guidance beam is conically scanned, and frequency modulated at the scan rate. If the missile detects an a-m signal, it will know that it is off the scan axis; if it detects no a-m signal, it will know that it is on the axis. The amplitude of the a-m signal indicates the size of the error. A large error will produce a large movement of the missile control surfaces. As the missile approaches the beam axis the error decreases, and the position of the control surfaces gradually returns to neutral, to prevent overshooting. The phase relation between the a-m and f-m signals indicates the direction of the error.

F. Limitations

8F1. General

Every mechanical or electrical system has limitations that cannot be exceeded. When working with complex mechanisms, such as guided missiles, it is as important to know limitations as it is to know the capabilities. Unless the limitations are known, a costly missile might be wasted.

One important limitation is the maximum range at which reliable control can be maintained. We have mentioned line-of-sight limitation. Bear in mind that this statement does not mean that the missile must remain within range of vision. It does mean that control may be lost if the path between the missile and the guidance radar extends over the horizon or is blocked by hills or mountains.

Another limitation, previously mentioned, is transmitter power. In theory, at least, any amount of power can be generated. Radar systems through pulse techniques, make it possible to get large peak power output while keeping the average power output within reasonable limits. Practical guidance systems have power limitations due to cost, size, and weight. Obviously, bulky equipment cannot be easily transported or installed aboard ships or aircraft. Therefore, a compromise must be reached to ensure useful results with equipment of reasonable size.

It should also be kept in mind that the radar beam increases in width and decreases in power as the range is extended, resulting in a decrease in both tracking and guidance accuracy at long ranges.

We have previously explained that countermeasures may decrease the effectiveness of an offensive weapon. The susceptibility of a guided missile to countermeasures is a limitation to its use. The effectiveness of countermeasure action can be greatly reduced by using coded-pulse modulation of the radar guidance beam.

CHAPTER 9
HOMING GUIDANCE

A. Introduction

9A1. General

In previous chapters, we have discussed guidance systems that are designed to place and hold a missile on a collision path with its target. As we have previously explained, missile guidance can be divided into three phases: launching, intermediate or midcourse guidance, and terminal guidance. The proper functioning of the guidance system during the terminal phase, when the missile is rapidly approaching its target, is of extreme importance. A great deal of work has been done to develop extremely accurate equipment for use in terminal-phase guidance.

This chapter will discuss some of the homing systems that have been found to be effective for terminal guidance, as well as some systems that, in their present state of development, have serious limitations.

The expression HOMING GUIDANCE is used to describe a missile system that can "see" the target by some means, and then by sending commands to its own control surfaces, guide itself to the target. (Use of the word "see" in this context does not necessarily mean that an optical system is used. It simply means that the target is detected by one or more of the sensing systems that will be described later in this chapter).

9A2. Basic principles

Some homing guidance systems are based on use of the characteristics of the target itself as a means of attracting the missile. In other words the target becomes a lure, in much the same manner as a strong light attracts bugs at night. Just as certain lights attract more bugs than others, certain target characteristics provide more effective homing information than others. And some target characteristics are such that missiles depending on them for homing guidance are very susceptable to countermeasures.

Other homing systems illuminate the target by radar or other electromagnetic means, and use the signals reflected by the target for homing guidance.

The various homing guidance systems have been divided into PASSIVE, SEMIACTIVE, and ACTIVE classes. The name of the class indicates the type of homing guidance in use.

If the target emits the homing stimulus, the system used to detect the target and guide the missile to it is known as a PASSIVE HOMING guidance system. One such system uses radio broadcast waves from the target area as signals to home on.

If the target is illuminated by some source other than itself or equipment in the missile, the system is known as a SEMIACTIVE HOMING system. For example, the target might be illuminated by equipment at the missile launching station.

If the target is illuminated by equipment in the missile, the system is called an ACTIVE HOMING guidance system. An example is a system that uses a radar set in the missile to illuminate the target, and then uses the radar reflections from the target for missile guidance.

9A3. Types of missile response

When the control surfaces of the missile are activated by one of the guidance systems, the missile is showing response to the guidance system. A number of guidance systems have been developed to respond to a variety of signal sources. These sources are:

SOUND. If we go through the frequency spectrum from low to high, we can list systems in order of frequency and start in the audio (low) range. Sound has been used for guidance of naval torpedoes, which home on noise from the target ship's propellers. But a guidance system based on sound is limited in range. The missile or torpedo must use a carefully shielded sound pickup, so that it will not be affected by its own motor noise. And while the speed of a torpedo is low compared to the speed of sound, most guided missiles are supersonic. Because of these limitations, no current missile uses a guidance system based on sound.

RADIO. Most homing guidance systems use electromagnetic radiations. Radio waves are used in one passive homing system. Homing is accomplished by an automatic radio direction finder in the missile. The equipment is tuned to a station in the target area, and the

missile homes on that station. This homing system is not restricted by weather or visibility. But it is unlikely that a radio transmitter would be operating under war conditions. In addition, radio jamming can do a most effective job of confusing a missile that uses radio for homing guidance. Our own Conelrad system, for example, is a technique for combating radio guidance systems. Under Conelrad conditions, every broadcasting station in the United States will switch to one of two assigned frequencies. Thus, a missile using radio homing guidance would receive signals from several directions at the same time.

While it is possible to do a thorough job of confusing a radio homing guidance system, there is one possibility that cannot be overlooked. The enemy must use electromagnetic systems for communications and search, and these systems can be used as a source of guidance signals. Also, it is possible for subversive agents to plant small, hidden radio transmitters in target areas.

RADAR. Although radar can be used for all classes of homing guidance, it is best suited for the semiactive and active classes. At present, radar is the most effective source of information for homing guidance systems. It is not restricted by weather or visibility, but under some conditions it may be subject to jamming by enemy countermeasure equipment.

HEAT. One form of passive homing system uses heat as a source of target information. Another name applied to this system is INFRA-RED homing guidance. Heat generated by aircraft engines or rockets is difficult to shield. In addition, a heated path is left in the air for a short time after the target has passed, and an ultra-sensitive heat sensor can follow the heated path to the object. One present limitation is the sensitivity of sensor units. As sensor units of higher sensitivity become available, infrared homing guidance will become increasingly effective. Such systems will make it difficult to jam the homing circuits, or to decoy the missile away from the target.

LIGHT. A passive homing system could be designed to home on light given off by the target. But, like any optical system, this one would be limited by conditions of weather and visibility. And it would be highly susceptible to enemy countermeasures.

9A4. Use in composite systems

In command and beam-rider guidance, the missile is controlled from the launching site, or from some other point at a considerable distance from the target. But neither of these systems is very effective against moving targets, except at relatively short ranges. The reason is obvious. The closer the missile gets to the target, the farther it is from its control point. At long range, a very small angular error in target tracking, missile tracking, or beam riding could cause the missile to miss its target by a wide margin.

Sidewinder is a Navy missile that uses homing as its only source of guidance. It has been used very effectively at relatively short range. But homing systems are based on information radiated from, or reflected by, the target itself. For targets at intermediate ranges, such signals are extremely weak, and could be used only by missiles with powerful and heavy guidance equipment. At long range, such signals are entirely unavailable.

An answer to this problem lies in the use of a composite guidance system. In this system, the missile is guided during its intermediate phase by information transmitted from the launching site, or other friendly control point. During the terminal phase, it is guided by information from the target. For intermediate-range missiles, either command or beam-rider guidance is suitable during the midcourse phase. A long-range missile would depend either on preset or navigational guidance to bring it to the target vicinity. Missiles of both classes can switch over to homing guidance, based on infrared or radar radiations, as they enter the terminal phase. At intermediate range, the switchover is usually accomplished by radio command. At long range, it is controlled by a navigational device, or by some form of built-in programing system.

The U. S. Navy missile program makes use of composite guidance systems in several of its operational missiles. Talos is a beam rider during its midcourse phase, and switches to radar homing for terminal guidance. Other missiles, such as Sidewinder, Sparrow, Petrel, and Tartar, use homing guidance systems in one form or another for terminal guidance.

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B. Passive Homing System

9B1. General

As mentioned earlier in this chapter, passive homing systems can be used when the target itself radiates information. Therefore, all of the response systems, with the possible exception of radar, might be used. The exception to radar would not apply if a signal from the target could be picked up by a radar set in the missile. This system would be unreliable; the only source of target information would be under enemy control, and could be switched off at will. But missiles using such a system would have one distinct advantage: they would deny the enemy the use of his own radar.

9B2. Basic principles

The passive homing systems most widely used at present are based on infrared radiation from the target. The sensing mechanism is so designed that it can determine the direction from which the infrared radiation is received; the guidance system can then steer the missile in that direction. There are several ways in which the sensing device can be made to determine the direction of an infrared source. For example, two sensors could be mounted with a baffle between them, so that the one on the right can receive radiation from straight ahead, or from any point to the right of the missile axis. The other sensor will receive radiation coming from the straight ahead or from the other side of the axis. When both sensors receive the same amount of radiation, the target is directly ahead. If the radiation is stronger on one side, the target is obviously on that side. A second pair of sensors could be used for up-and-down steering.

Another infrared passive homing system makes use of a sensing device mounted in gimbals, and driven by servo mechanisms. The system is so designed that the sensing device will constantly track the target. Thus, the axis of the sensing device, in relation to the axis of the missile, provides the required information for steering.

9B3. Target characteristics

In passive homing, the target itself must provide all the necessary information for missile guidance. For this reason the characteristics of an individual target will determine which types of homing system can be used against it, and under what conditions they can be used.

If the target is fixed in location, and has some characteristic by which the missile can readily distinguish it from the surrounding area, the homing guidance problem is simplified. Figure 9B1 represents an air-to-surface or surface-to-surface missile, using a light-sensing guidance system to home on an industrial building. While such a missile might be useful in a surprise attack, industrial plants would certainly be blacked out during a war. A light-homing missile would then have no way to distinguish the target from its background. But infrared passive homing could be used in this application. And it would probably be more effective than light-homing, since the heat generated by an industrial plant can not be readily controlled.

Figure 9B2 represents a passive infrared homing missile attacking an aircraft. The Navy's Sidewinder uses this type of guidance. The tailpipe of a jet aircraft is a strong source of infrared radiation, which cannot be

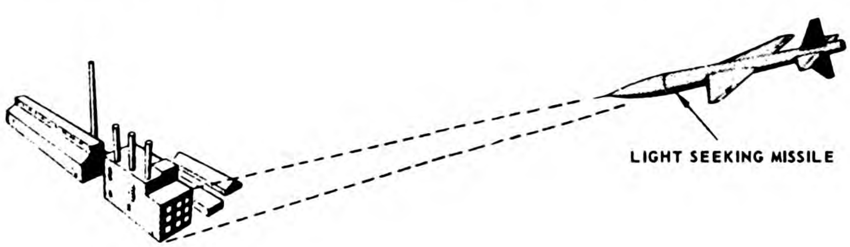

Figure 9B1.—Missile using light-homing guidance.

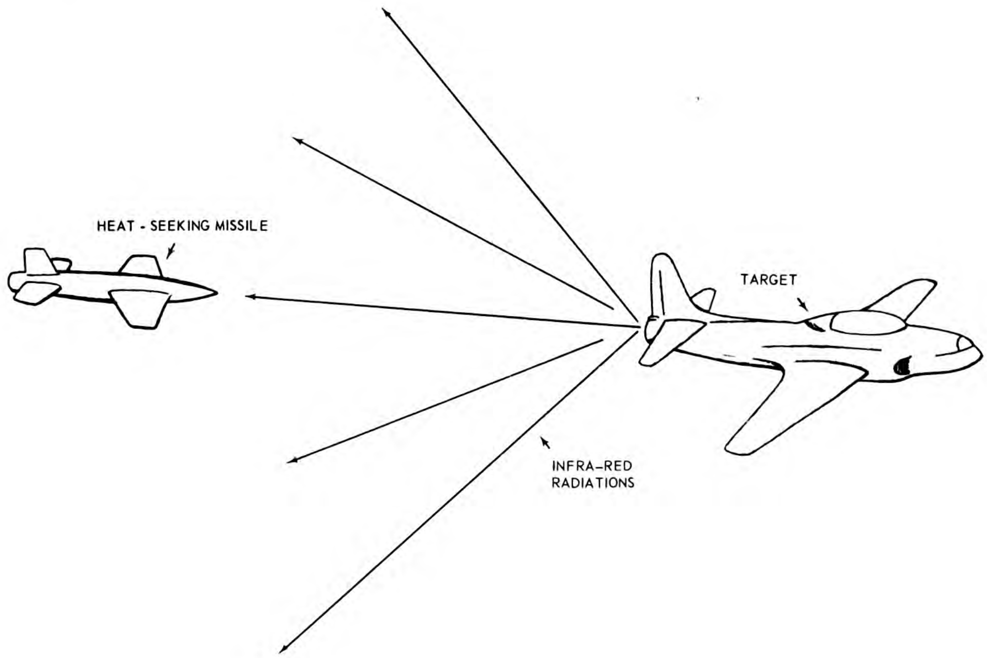

Figure 9B2.—Missile using heat-homing guidance.

concealed. In a tail-chase attack, the Sidewinder is highly effective. Against an approaching jet aircraft, Sidewinder and similar missiles are of little use.

A sound-homing system might also be used against a jet aircraft target, even though both target and missile are traveling faster than sound. Such a system might be used in a tail chase, provided the target does not maneuver radically. But you have probably observed that when a jet passes over at moderate altitude, the sound appears to come from a point at some distance behind the aircraft. A sound-homing missile would steer itself toward the source of sound, rather than toward the target itself. For an approaching or crossing target, the required trajectory would be too sharply curved for the missile to follow.

9B4. Missile components

When passive homing guidance is used, the missile must contain all of the equipment needed to pick up, process, and use the information given off by the target. The kind and amount of equipment required is determined to a large extent by the guidance system used, and by the characteristics of the target. Consideration must also be given to: the maximum range, information required, accuracy, operating conditions, type of target, and speed of the target. The components of the guidance system in the missile can be sectionalized for separate discussion. We will explain the purpose of each section. Figure 9B3 shows a block diagram of a passive homing guidance system.

ANTENNA OR OTHER SENSOR. Since information given off by the target is to be used for guidance, some means must be provided to pick up the information. For electromagnetic systems, a conventional radio or radar antenna (streamlined into the missile) would be used.

A heat-sensing detector, rather than an antenna, is used with infrared homing guidance systems. One of the basic heat detectors is called a THERMOCOUPLE. When two dissimilar metals, such as iron and copper, are joined and heat applied to the junction of the two metals, a measurable voltage will be generated between them. Figure 9B4 shows a basic thermocouple.

The voltage difference between the two metals is quite small, but the sensitivity can be increased to a point where the thermocouple becomes useful as a detector of heat. The

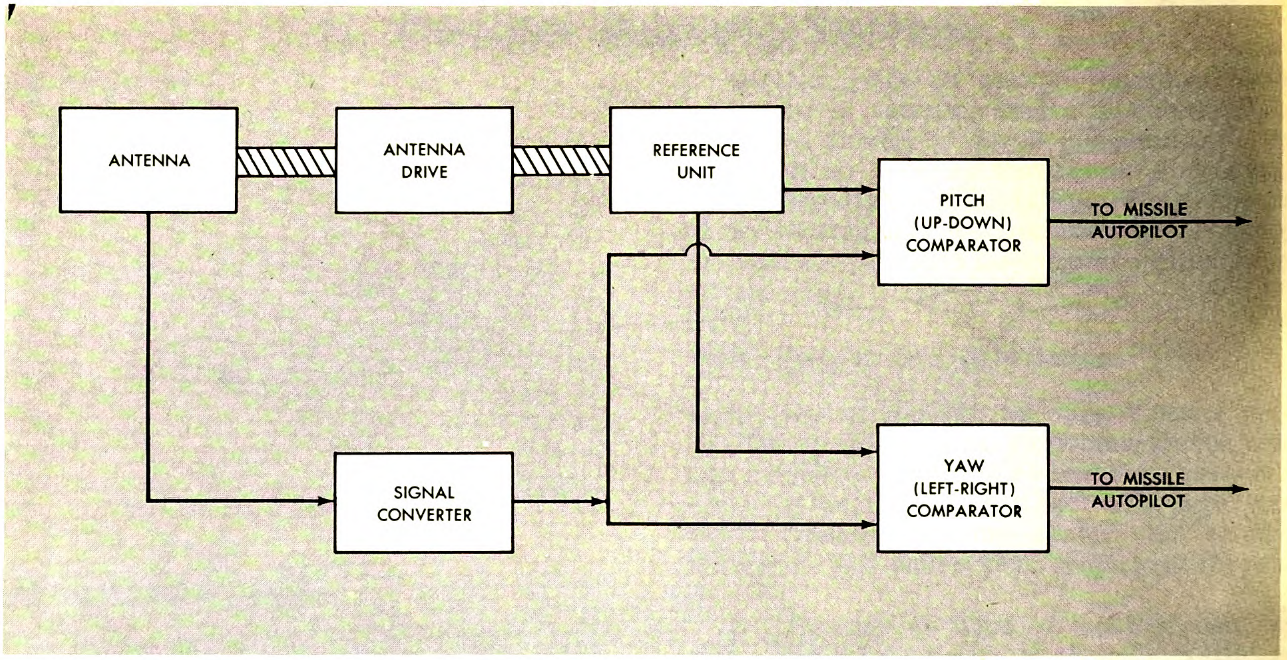

Figure 9B3.—Block diagram of passive homing guidance system.

increase in sensitivity is obtained by connecting, or stacking, a number of thermocouples in series, so that they form what is known as a THERMOPILE. The complete thermopile action is similar to that obtained when a number of flashlight cells are connected in series. That is, the output of each individual thermocouple is added to the output of the others. Thus ten thermocouples, with individual output voltages of .001 volts, would have a total output of .010 volts when connected in series.

The sensitivity of a thermopile heat detector can be further increased by mounting the thermopile at the focal point of a parabolic reflector. When this method is used, heat rays given off by the target are focused on the thermopile by the reflector.

Another type of heat detector is called a BOLOMETER. This device depends on the change of electrical resistance of a material when heated. In a simple type of bolometer, two thin strips of platinum are used to form two arms of a Wheatstone bridge. To increase the thermal sensitivity of the strips, each is blackened on one side. The heat to be measured is applied to one of the strips, and is absorbed by its blackened surface. As the strip absorbs heat, its resistance changes and unbalances the bridge. This unbalance causes a change in the current produced by an external voltage applied to the input terminals of the bridge.

Figure 9B5 shows a modern bolometer; it consists of four nickel strips supported by phosphor bronze springs. These springs are supported by mounting bars, which have electrical connection leads attached to them. A silvered parabolic reflector (mirror) is used to focus infrared rays on the bolometer. The bridge unbalance current, produced as a result of resistance changes, is used to set in motion the other sections of the guidance system.

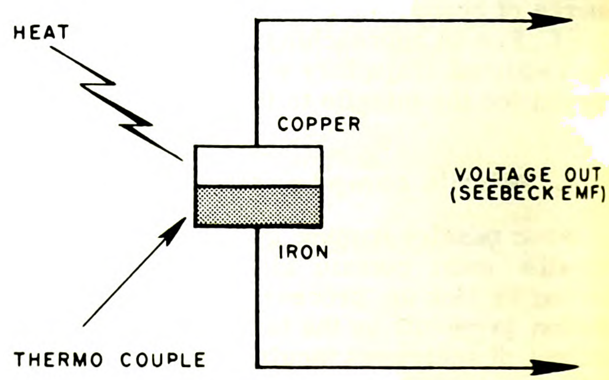

Figure 9B4.—A basic thermocouple.

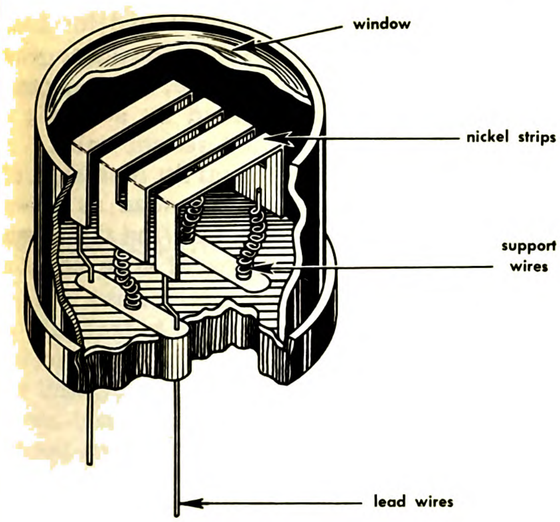

Figure 9B5.—Modern bolometer.

Still another form of infrared detector is shown in figure 9B6. It is called a GOLAY DETECTOR. This detector is a miniature heat engine. The Golay heat cell operates on the principle that a pressure-volume change occurs in a gas when its temperature is changed. At the forward end of the cell is a metal chamber which encloses the gas. The front of the chamber is covered by a membrane, which acts as a receiving element. The back of the chamber is closed by a flexible mirror membrane. When radiant heat strikes the receiver, it raises the temperature of the gas in the chamber. The resulting increase in pressure distends the mirror membrane. Light from a small exciter lamp (fig. 9B6) is focused by a lens, and then passed through a grid of parallel lines. The light is then reflected by the mirror membrane, back onto the grid.

When the mirror membrane is not distended, it reflects the image of the open spaces in the grid back onto the opaque lines of the grid. Thus no light can pass back through the grid. But when the mirror membrane is distended, the image of the open spaces in the grid passes back through those same open spaces. Thus the amount of light passing back through the grid provides an indication of how much the mirror membrane is distended, and, indirectly, of how much heat is reaching the detector.

A part of the light that passes back through the grid is reflected downward by a diagonal mirror (shown at the lower right in fig. 9B6). This light is then picked up by a photoelectric cell. The output of the photo cell thus provides an indication of radiant heat entering the detector. The device is quite sensitive, since a small amount of mirror distortion produces a considerable change in photo cell illumination. The Golay detector has the most rapid response of any infrared detector, but it can operate only when radiant heat is received intermittently. For some guidance systems this factor makes the Golay detector useless; in others it causes no difficulty.

In the light-homing guidance systems, the pickup device or sensor is a photoelectric cell. The operation of this device is based on the fact that certain metallic substances emit electrons when they are exposed to light. Modern photoelectric cells are quite sensitive to light variations; but, because light is easily interrupted, the system is subject to interference. One type of photoelectric cell is shown in figure 9B7.

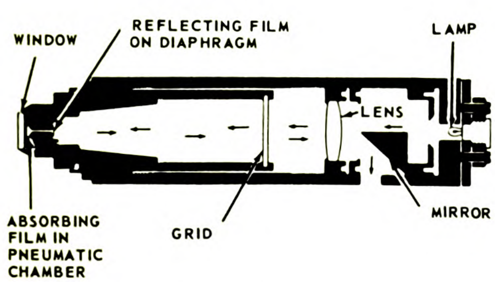

Figure 9B6.—A Golay detector.

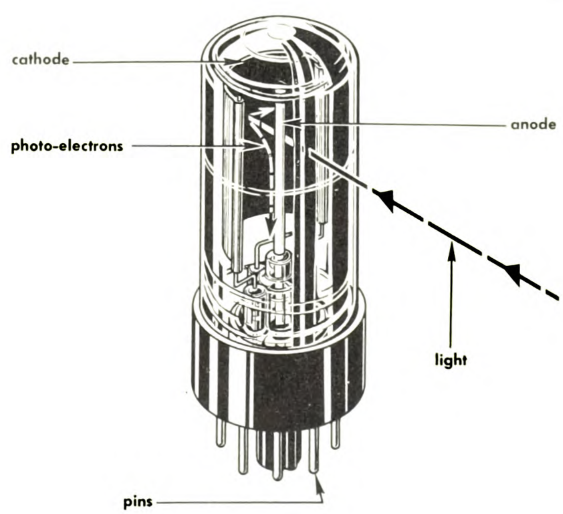

Figure 9B7.—A photoelectric cell.

The objection to photoelectric cells has been partially removed by the recent development of cells with a sensitivity in the infrared region. However, the extension of the range of operation changes the sensor from a pure photoelectric device to a thermoelectric device. It is then similar in operation to a heat sensor.

ANTENNA OR SENSOR DRIVE. Previous chapters have described antenna scanning methods. The reflectors mentioned for heat or light homing sensors act in the same way as a radar reflector. Therefore, greater control accuracy can be obtained by scanning a target with the reflector and sensor units.

Should the sensor temporarily lose sight of the target, a spiral or sawtooth scan, as shown in figure 9B8, could be used to find the target again. Notice that both types of scan cover a large area.

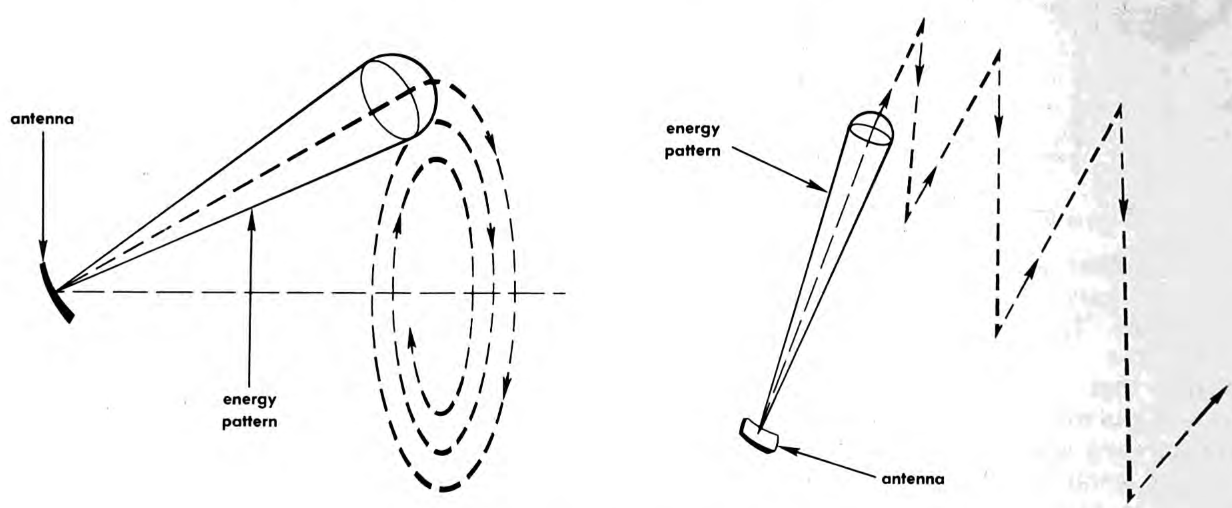

Figure 9B8.—Spiral and sawtooth scanning.

The scanning action is controlled by the antenna or sensor drive unit, which is shown in the block diagram of figure 9B3.

After the antenna or sensor has picked up the information, other equipment in the missile must convert the information into error signals, if the missile is off course. Before this can be done, however, there must be something to compare with the sensor signal.

REFERENCE UNIT. The comparison voltage is taken from the reference unit. This voltage may be obtained from an outside source, or it may be taken from recorded information that was put into the missile before launching. Actual operation of the missile guidance controls takes place only when an error signal is present. Note that the reference unit is connected to both the pitch and yaw comparators in the block diagram of figure 9B3.

SIGNAL CONVERTER. The output of the sensor unit is an extremely small voltage. This voltage is fed to a signal converter, which builds up the strength of the signal and interprets the information contained in it. The output of the signal converter is fed to the pitch and yaw comparators along with the signal from the reference unit.

COMPARATORS. The comparators are electronic calculators that rapidly compare reference and signal voltages and determine the difference (error), if any, between the two signals. It is possible for an error signal to be developed in the pitch comparator while no error signal is developed in the yaw comparator. Should this happen, the missile would be higher or lower than the desired trajectory. The output voltage from the pitch comparator is then fed to the missile automatic pilot.

AUTOPILOT. The automatic pilot, or autopilot, operates missile flight controls in much the same way as a human pilot operates airplane controls. The components making up the autopilot assembly have been described elsewhere in this text. In order to shift the flight controls, the autopilot must get "orders" from

some circuit. The orders are in the form of error signal voltages from the comparators. The error signal voltages operate motors or hydraulic valves which, in turn, operate the flight control surfaces.

C. Semiactive Homing System

9C1. Basic principles

In a semiactive homing system, the target is illuminated by some means outside the target or the missile. Normally, radar is used for this type of homing guidance, by sending a radar beam to the target. The beam is reflected from the target, and picked up by equipment in the missile. The radar transmitter might be located at a ground site, or it might be a mobile unit aboard a ship or aircraft.

9C2. Launching station components

In a semiactive homing guidance system, the launching station components are similar to those required for a beam-rider guidance system (chapter 8). The target is tracked by radar. The tracking radar itself may be used as the source of target illumination for missile guidance, or a separate radar may be used for this purpose.

9C3. Missile components

The missile, throughout its flight, is between the target and the radar that illuminates the target. It will receive radiation from the launching station, as well as reflections from the target. The missile must therefore have some means for distinguishing between the two signals, so that it can home on the target rather than on the launching station. This can be done in several ways. For example, a highly directional antenna may be mounted in the nose of the missile, as noted below. Or the doppler principle may be used to distinguish between the transmitter signal and the target echoes. Since the missile is receding from the transmitter, and approaching the target, the echo signals will be of a higher frequency.

For the purposes of this text, we can think of the missile guidance components as divided into several distinct sections. These are shown in block diagram form in figure 9C1.

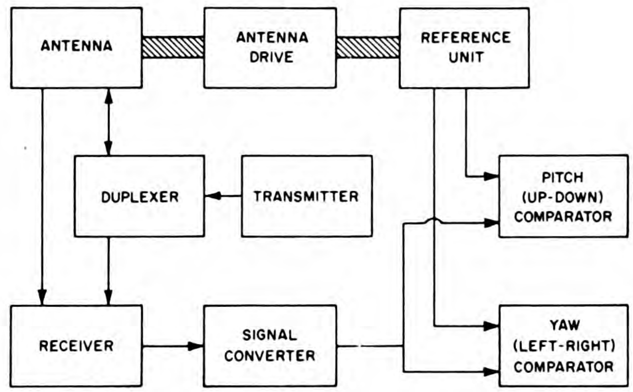

Figure 9C1.—Block diagram of semiactive homing system.

ANTENNA. Radar is generally used for semiactive homing guidance. The antenna in the missile must therefore be capable of detecting radiation at radar frequencies. It is mounted in the nose of the missile, since information is being obtained from the target area and the missile is approaching the target nose first. When a beam-riding system is used for the intermediate phase of guidance, a separate beam-rider antenna is mounted near the tail of the missile.

ANTENNA DRIVE. In some systems, the homing guidance antenna may use a form of conical (or nutating) scan in order to take full advantage of the guidance signal. Conical scanning has the advantage that the antenna can receive signals from points off the missile axis. This decreases the chance that the missile, while homing, may lose its target and go out of control.

RECEIVER. A radar-type receiver must be used in the missile when radar is used for semiactive homing. The signals picked up by the antenna as it scans the target area are fed into the receiver. The receiver operates in a conventional manner as described in chapter 7. The signals at the output of the receiver are not suitable for use in activating the missile flight controls without further processing.

SIGNAL CONVERTER. The receiver output is fed to the signal converter, which changes the signal to a form that can be used

for comparison with signals from another section of the missile electronic equipment.

REFERENCE UNIT. The reference unit furnishes the comparison signal. This information might be placed in the missile just prior to launching. It could be stored in a variety of forms, such as magnetic wires, magnetic tapes, punched paper tapes or punched cards. Before a guidance system can function, an error signal must be produced. The error in flight path, if any, can be determined by comparing the reference signal and the signal from the converter section. Comparison of the two signals takes place in other sections of the missile electronic equipment.

COMPARATORS. The missile flight controls may be used to correct the lateral or vertical trajectory of the missile. Since it is possible for the missile to be on the right course vertically but off course laterally, two comparators are used. The output from the reference unit and the output from the signal converter are fed to both the pitch and yaw comparators.

Should there be no difference in the two signals at either comparator, the controls would remain in neutral position. However, should there be a difference in the two signals at either comparator, error signals will be generated. The error signals are not suitable for use in controlling the missile flight surfaces and must be sent to other sections of the guidance system before they can be used.

AUTOPILOT. The missile flight control surface operation is controlled by autopilots. These devices are a combination of gyroscopes and electrical units which have been described elsewhere in this manual. The autopilot controls operation of the hydraulic system which, in turn, operates the flight control surfaces. There are two autopilots—one for the pitch control surfaces and one for the yaw control surfaces.

9C4. Comparison with passive homing

The passive guidance system obtains all guidance information from the target, without assistance from any other outside source. The semiactive homing system needs some source outside the target or missile in order to obtain course information.

The advantage of the passive system is that it needs no source of information other than the target. The equipment carried by the missile is less than that required for most other systems. The disadvantage of the passive guidance system is its dependence on the target. It is highly unlikely that an enemy would leave target areas lighted, or permit electromagnetic forms of broadcasting from the target areas.

In the semiactive system, control information comes from a source outside the missile or target area. A semiactive homing system depends for guidance on equipment outside the target area or the missile. This requires extra equipment, both in the missile and at the launching or control point. Semiactive homing systems, like most guidance systems, are subject to jamming and other forms of interference.

D. Active Homing Guidance

9D1. Basic principles

The active guidance system uses equipment in the missile to illuminate the target, and to guide the missile to the target. Usually, a radar set is used for target illumination. The signals return to the missile as radar echoes, which are processed for use as guidance signals.

9D2. Missile components

The missile components in an active homing guidance system include all those used in a semiactive homing guidance system, plus a radar transmitter and duplexer. The principal components are shown in the block diagram of figure 9D1.

ANTENNA. The antenna is the same as described for the semiactive system, and is mounted in the nose of the missile.

ANTENNA DRIVE. When the target area is conically scanned, the antenna driving unit provides the power needed for this purpose.

TRANSMITTER. The transmitter carried in the missile is similar to a conventional radar transmitter. It may use either FM or pulsed modulation. Since homing guidance does

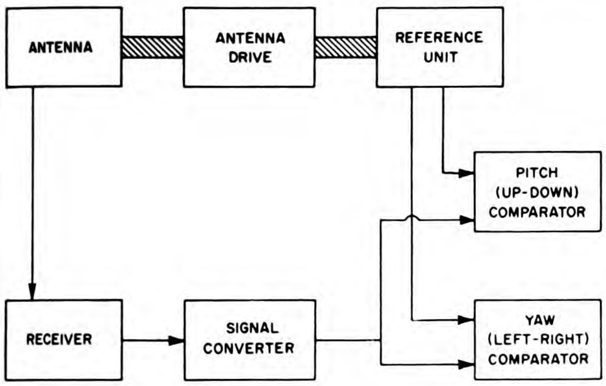

Figure 9D1.—Block diagram of active homing guidance system.

not require long range equipment, the transmitter power can be considerably less than that used for command guidance or tracking. The method of modulating the transmitter can be changed frequently to lessen the effectiveness of enemy countermeasures.

DUPLEXER. The duplexer is a form of electronic switch. In operation, it serves to connect the antenna to the transmitter during the sending of a pulse. At the same time, it presents a high impedance (electrical opposition) at the receiver input. This keeps the powerful transmitter pulse from damaging the receiver.

As soon as the pulse is transmitted, the duplexer then offers a low impedance path from the antenna to the receiver. The action of the duplexer provides an automatic switching means, so that the same antenna can be used for both transmitting and receiving.

REFERENCE UNIT. The reference unit in the active homing guidance system serves the same purpose as those in the passive and semiactive homing guidance systems.

SIGNAL CONVERTER. The output of the receiver is fed to the signal converter, so that the reflected signal will be suitable for comparison with the output of the reference unit. The purpose and operation of the signal converter is the same as for the semiactive homing guidance system.

COMPARATORS. The comparators serve the same purpose as those in the semiactive system.

AUTOPILOT. The missile flight controls are operated by the hydraulic system, which is activated by the autopilot in the same way as described for the semiactive system.

9D3. Comparison with semiactive homing system

The active homing guidance system may be used in any application where the target can be distinguished from the surrounding area by the radiation it reflects. Of course, the more prominent the target, the greater the accuracy of homing guidance.

An advantage of the active homing guidance system is its independence from any outside source of target illumination. At the same time, this is a disadvantage because of the added equipment needed in the missile. Also, the system is subject to countermeasures. But this problem is less serious than it might be, because the homing guidance equipment is active for only a relatively brief part of the missile's flight time.

E. Homing Trajectories

9E1. Zero-bearing course

A homing missile uses one of two methods in approaching a target. When the missile flies directly toward the target at all times, the trajectory is known as a ZERO BEARING or PURSUIT approach.

All of the homing guidance systems we have described have had the sensor unit (thermopile, light cell, microphone, or antenna) mounted in the nose of the missile. The sensor is fixed to the missile frame so that it maintains a constant relationship to the missile axis. The equipment in the missile is then able to process the information picked up by the sensor, so that the missile can be continually pointed toward the target. A possible flight path for a ground-to-air missile is shown in figure 9E1. Notice how the flight path must curve as the missile approaches the target. The sharp curvature in the path sets up strong lateral accelerations during the terminal

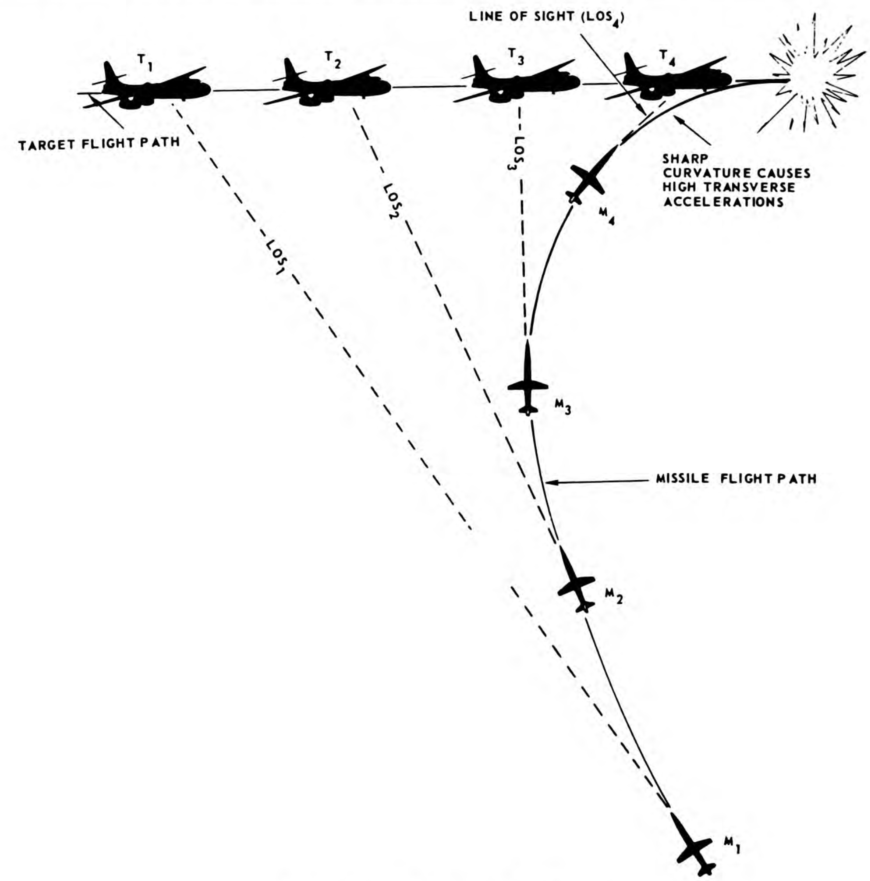

Figure 9E1.—Zero bearing flight path.

phase of flight. These transverse accelerations present a strong objection to the use of a zero-bearing approach against high-speed air targets.

Another objection to the zero-bearing approach system is that the missile speed must be considerably greater than the target speed. As shown in figure 9E1, the sharpest curvature occurs near the end of the flight. At this point, the missile is "coasting" because the booster and rocket motor thrusts last for only a short part of the flight.

More power is required to make sharp radius, high speed turns at a time when the missile is losing speed and has least turning capability. Often the amount of turn required is beyond the aerodynamic capability of the missile at that time, and the missile therefore cannot hit the target.

9E2. Lead angle or collision course

The second method of approach to the target is called LEAD ANGLE course. It is also known as a CONSTANT BEARING or COLLISION course. The trajectory of a ground-to-air missile using this method of approach is shown in figure 9E2.

Notice that the missile path from the launcher to the collision point is a straight line. The missile has been made to lead the target in the same manner as a hunter leads a bird in flight. In order to lead the target and obtain a hit, a computer must be used. The computer continually predicts the point of missile impact with the target. If the target takes no evasive action, the point of impact remains the same from launching time until the missile strikes. Should the target take evasive

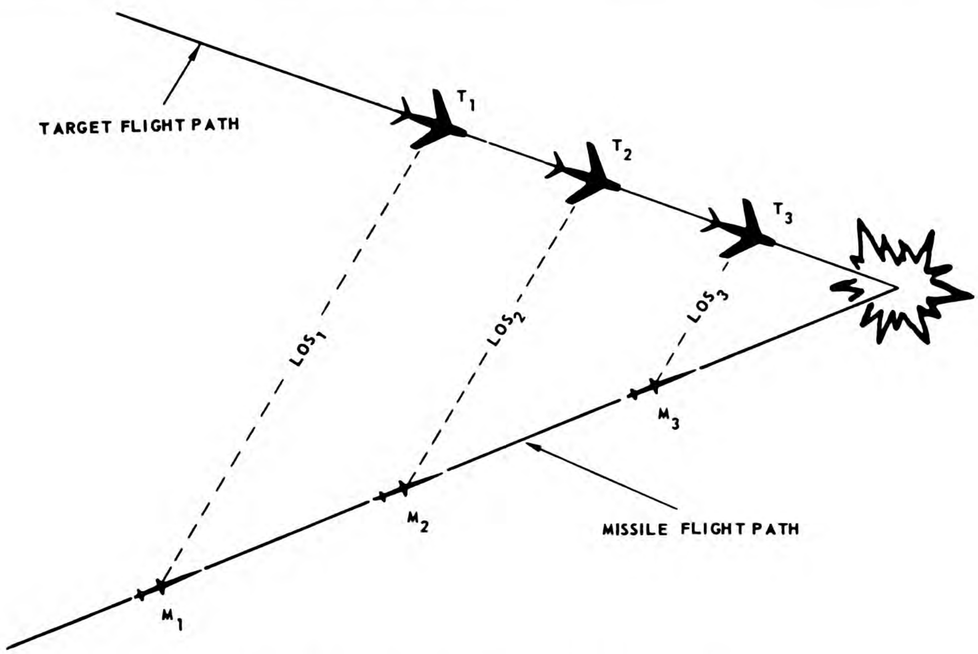

Figure 9E2.—Lead angle method of approach.

action, the computer automatically determines a new collision point. It then sends signals to the autopilot in the missile, to correct the course so that it bears on the new collision point.

As shown in figure 9E2, the collision point and the successive positions of missile and target form a series of similar triangles. If the missile path is the longer leg of the triangle, as it is in the figure, the missile speed must be greater than the target speed—but not as great proportionally as with a zero-bearing approach.

The transverse acceleration required of a missile using the lead-angle approach is comparatively small.

CHAPTER 10

OTHER GUIDANCE SYSTEMS

A. Preset Guidance

10A1. Introduction

In earlier chapters we described guidance systems in which the missile trajectory depends on information received from one or more control points, or from the target itself. But, under certain conditions, these systems are impractical. This is especially true for long-range missiles. In this chapter, we will discuss several guidance systems, in which the missile is independent of control points and target signals.

Perhaps the simplest of these is the PRESET GUIDANCE system. The name is completely descriptive. In this system, all the information needed to make the missile follow a desired course, and terminate its flight at a desired point, is set into the missile before it is launched. This information includes the desired heading, altitude, time or length of the flight, and programmed turns (if any).

Preset guidance may be used when the target is beyond the range of control points, or when it is necessary to avoid countermeasures that might be effective if the missile were guided by outside signals.

In setting up a flight plan for preset guidance, missile speed is used to determine the required time of flight. Assume, for example, that a missile is to be fired at a target 500 miles north of the launching site. The direction and distance of the target from the launch site have been accurately determined. Assume that the speed of the missile can be controlled, or at least can be predicted with enough accuracy to program the flight.

If we assume an average missile speed of 2000 miles per hour, the missile would require 15 minutes to travel from the launch site to the target. The built-in control system would take the missile to cruising altitude, keep it headed north for 15 minutes, and then move its flight surfaces to make it dive straight down on the target.

Preset guidance has several limitations. Such things as headwinds and crosswinds will obviously affect the speed and course of the missile. To compensate for the effects of wind, the missile would need some means for measuring its ground speed, and for changing its air speed as required. But, when solid fuels are used, changing the air speed of the missile is difficult.

Crosswinds may exist at one altitude but not at another. Thus the altitude at which a missile operates may have a pronounced effect on its course. If the effect of wind on missile heading cannot be controlled by choice of altitude, then it must be controlled by programmed steering of the missile. One of the greatest limitations of a preset guidance system is that the flight program cannot be changed after the missile is launched. Therefore precise information on winds along the missile flight path will be needed for accurate programming.

10A2. Information set in the missile

The initial course or heading of the missile may be preset by training the launcher. This operation is similar to that of training a gun. However, once the missile is started on the correct heading, its own equipment takes over. References may be used to determine deviations from the preset course, and to keep the missile headed in the right direction. For example, the flight might be programmed to use the earth's magnetic field to keep the missile headed toward magnetic north, or in some other specified direction.

The missile altitude may be corrected by changing the pitch of the missile. A barometer-type sensing element is connected to a servo mechanism that operates the flight control surfaces. When the barometric pressure changes because of a change in altitude, the servo acts to bring the pressure back to the preset value by correcting the missile's altitude. Although this method of altitude control is not extremely accurate, the control pressure can be preset to fairly close tolerances before the missile is launched.

One of the most precise components of a preset guidance system is its timing section. Accurate timing elements are available to fit almost any requirement. The distance covered by a missile during its flight is determined by its ground speed and the length of time it is in

the air. Therefore, if the speed of the missile is known, the controls may be preset to dive the missile at the end of a definite time interval after launching. The timing element can be anything from a simple watch movement to an electronic circuit controlled by a tuning fork or a crystal oscillator. The time interval may be set at any time before launching, but of course it cannot be changed during flight.

It is possible to program changes in course, and timing circuits may be used to set up the program. For example, the missile could follow a due north course for 15 minutes, then turn 30 degrees east, and follow the new course for 10 minutes before starting its terminal dive on the target. In another case, to provide deception, the missile might be programmed to fly due north for 10 minutes, then 30 degrees east for 5 minutes before turning 30 degrees west to get back on the original heading.

10A3. Heading reference

The missile control systems must have a reference from which to measure the up-down or right-left deviation of the missile. Since the desired heading is a compass direction, the sensing unit may be a form of compass.

In an earlier chapter we described the flux valve and its uses in control systems. If magnetic headings are to be followed, the flux valve may be used as the sensing element. By using a time reference in combination with a magnetic reference, the missile controls may be preset to follow a single heading for required time. Or changes in heading can be programmed to occur at preset times.

The electrically driven gyro is another type of heading control. The gyro's spin axis is tangent to the earth's surface. At the time of launching, with the gyro wheel spinning rapidly, the axis is pointed in the desired direction before the gyro is uncaged. During the missile flight the gyro axis continues to point in the original direction, and the missile can therefore use it as a steering reference.

10A4. Altimeters

In previous chapters we have shown that an altimeter can be used to control missile altitude within small limits. Altitude control is an important part of preset guidance, since it is possible to get favorable wind direction or avoid unfavorable winds by choosing the proper altitude.

The reference for preset altitude control is normally a potentiometer in one arm of a bridge circuit. A potentiometer in an adjacent arm of the bridge is operated by a pressure-sensitive bellows system. The bridge can be preset for balance at the desired altitude. When the missile reaches the preset altitude, its flight control surfaces will bring it into level flight. Any subsequent change in pressure will unbalance the bridge, and the amount and direction of unbalance will determine the correction to be applied. This system will be described in more detail later in this chapter.

10A5. Length of flight

In low-speed missiles an AIR LOG, as well as a timing device can be used to measure the distance covered during missile flight. The air log operates on the principle of an air screw, or impeller, which makes a specific number of revolutions while moving through the air for a given distance at a given speed. The number of revolutions per unit of distance depends on both the pitch of the blades and the density of the air.

Generally, an air log is attached to the outer surface of the nose of the missile, and consists of a small four-bladed impeller mounted on a shaft that drives a reduction gear with a ratio of 30 to 1; that is, for every 30 revolutions of the air screw, the driven gear makes 1 revolution.

The driven gear is made of insulating material, and carries a pair of contacts mounted at diametrically opposite points. These contacts close a magnetic relay circuit twice in each revolution of the gear, or once for each 15 revolutions of the air screw.

The magnetic relay is connected to a device called a Veeder counter. The counter mechanism is similar to that of the total mileage indicator (odometer) of an automobile. The Veeder counter is shown in cross-section in figure 10A1.

To use the air log for length-of-flight regulation, the calibrated drums are turned to a setting that represents the desired distance of travel for the missile. Each time the contacts of the magnetic circuit close, they trip the counter mechanism, thus indicating that a

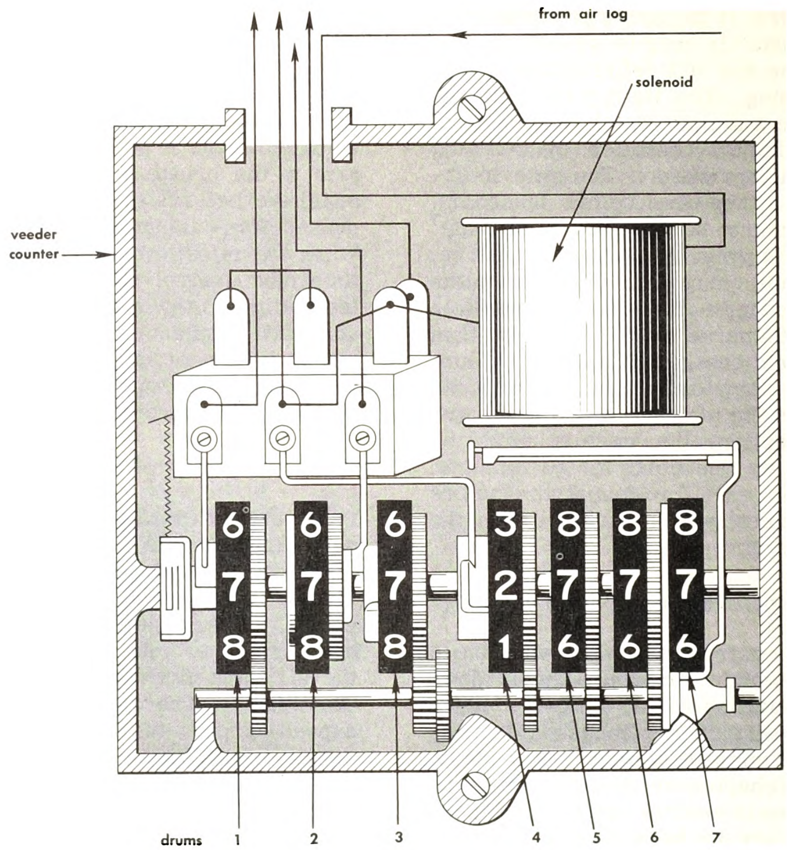

Figure 10A1.—Veeder counter cross-section.

certain specific distance has been traveled. Each time the mechanism is tripped, it moves the drums back one digit from the preset figure. When the count reaches zero, the predetermined destination has been reached. This may be either the point where the warhead is to be detonated, or the point at which the missile is to start its terminal dive on the target.

In the preceding discussion, we have shown how a digital counter is used to measure flight distance. Now let us see how air speed may be measured and controlled.

Figure 10A2 is a diagram of an air speed reference and transducer unit. The resistors R1 and R2 are identical potentiometers. Together they form the four arms of a resistance bridge.

The moving arm of R1 is mechanically driven by a bellows, which is connected to a tube leading to the nose of the missile. As the missile moves through the air, ram air pressure is built up in the bellows. The amount of pressure is determined by the air speed.

In operation, R2 is preset to a value that represents the desired air speed. When the moving arm on R1 is in the same position as that of R2, the bridge is balanced and there is no output. Because the arm of R1 is connected to the bellows, the bridge will be balanced whenever the ram air pressure equals the preset value. For perfect operation, the movement of R1 must be proportional to the change in air speed. This is difficult to achieve in practice. But because the missile speed needs to be constant only within certain limits, the

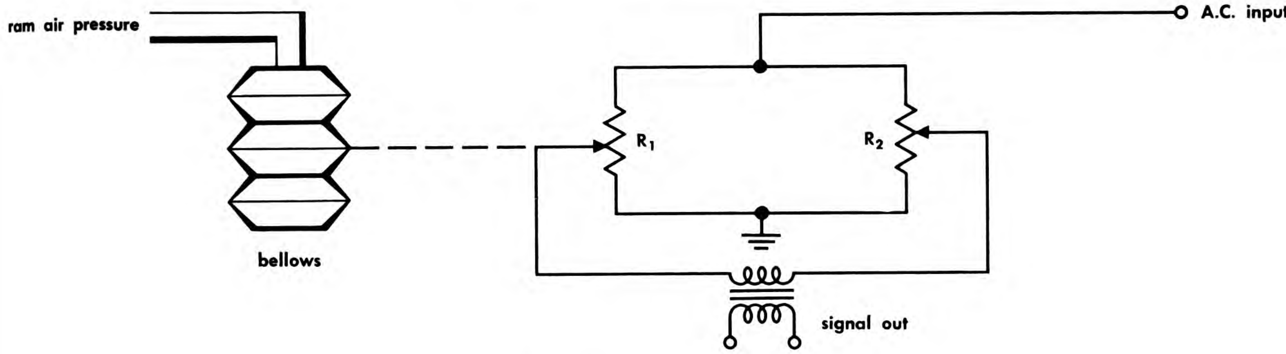

Figure 10A2.—Air speed transducer.

required accuracy can be obtained with presently available components.

When the bridge becomes unbalanced because of a change in ram air pressure, current will flow through the primary winding of the output transformer. The magnitude of the voltage induced in the transformer secondary is determined by the amount of bridge unbalance, which in turn is determined by the ram air pressure. The output voltage is used to operate the throttle controls. This system serves as both an air speed detector and a fixed reference; speeds either above or below the preset value will produce an output signal, and cause the throttle to correct the error.

10A6. Use in composite systems

A composite guidance system is made up of two or more individual guidance systems. These systems may work together during all phases of the missile's flight, or they may be programmed to operate successively. It is sometimes necessary to combine systems because of the wide differences in requirements that must be met to ensure that the missile reaches the target. Let us review these requirements, to see how preset guidance may be used in a composite system.

During the launching period, high acceleration puts a great strain on normal guidance components and prevents their use. The acceleration forces may close relays, precess gyros, and saturate accelerometers far beyond the sensitivity needed for normal guidance. For this reason, most midcourse guidance systems must be modified extensively to withstand the launch acceleration. The modification may involve the use of comparatively insensitive components, or a temporary alteration of the regular components.

The precautions against high acceleration damage to components include careful balancing and positioning of elements that are not used during the launch cycle. In addition, movable parts of regular guidance systems are locked in position, or the circuits in which they operate are neutralized to withstand the launch acceleration.

Missiles are designed to have sufficient flight stability during the initial period of high acceleration, before the regular guidance system takes over. The regular guidance system may be unlocked by an internal timer, or it may be activated when the booster section, if any, drops off.

A preset guidance system might be used for the midcourse part of a flight. When used in a composite system, the preset system would turn the missile control over to a separate terminal guidance system when the missile approaches the target. In an application of this type, the preset guidance system might be set up to take over control again in the event the terminal guidance system did not operate. Then, when the missile reached the approximate location of its target, the preset guidance system would either detonate it or cause it to dive, depending on the setting.

10A7. Ballistic missiles

A ballistic missile is a guided missile which, during a major part of its flight, is neither guided nor propelled. During this part of the flight it follows a free ballistic trajectory, like a bullet or a thrown rock. A number of factors operate to determine the

trajectory of a bullet, a rock, or a ballistic missile. These factors include the point of origin, the initial direction and velocity, air pressure, wind, and other factors mentioned in chapter 2 of this text. If all of these factors are accurately known, it is possible to calculate the point at which the ballistic object will strike the earth. And, if the desired point of impact is a target at a known location it is possible, for any given launching point, to calculate an initial course and velocity that will result in a hit.

A gun projectile is, of course, a ballistic object. The location of gun and target, and the initial velocity of the projectile, are known quantities. Factors such as wind and air pressure can be estimated. It is then possible to calculate the initial direction required for a hit, and, by pointing and training the gun, to fire the projectile in that direction.

The ballistic missile presents a more complex problem. Its range may be measured in thousands of miles, rather than thousands of yards, and its initial velocity is lower than that of a gun projectile. Thus the forces that would tend to influence its trajectory have a much longer time to act. But, at long ranges, ballistic missiles have several outstanding advantages. First, they leave the earth's atmosphere completely; a large part of their flight is in empty space, where they cannot be affected by wind or air pressure. Second, they dive on the target at a steep angle, at many times the speed of sound; this makes interception nearly impossible. Finally, a ballistic missile is invulnerable to electronic countermeasures during the major portion of its flight. Any guided missile is subject to jamming or deception by electronic countermeasures, although coded guidance systems may make this difficult to do. But a ballistic missile, because it is unguided during the terminal phase of its flight, is no more susceptible to electronic countermeasures than is a gun projectile or a rock.

The IRBM and ICBM are, as their names tell you, ballistic missiles. These include ATLAS, THOR, and POLARIS. Other missiles, such as SNARK, have comparable ranges, but are not ballistic missiles because they do not leave the atmosphere, and are propelled and guided throughout their flight.

The foregoing discussion of preset guidance applies principally to aerodynamic missiles, in which the control surfaces are capable of correcting the trajectory throughout the flight. But preset guidance has features that make it useful in the initial control of ballistic missiles. One possible ballistic system combines features of both preset and command guidance. The problem has already been stated: from known factors, it is possible to calculate an initial velocity and direction that will produce a ballistic trajectory ending at the target. The target location is known; because of the great range, target location is determined from maps, rather than by observation. The location of the launching point is also known. (In the development of the Polaris missile system, a major part of the total effort was devoted to development of a Ship's Inertial Navigation System, by which the Polaris launching vessel can determine its own position with the required accuracy.)

But other factors, such as air pressure and wind at various altitudes, cannot be determined with comparable accuracy. And, because of the extreme range, a small error in the initial direction or velocity will result in a large error at the target. The ballistic missile system deals with this problem by controlling the missile's direction and velocity not at the instant of launching, but at a later time—after the missile has risen above most of the atmosphere, but while it is still within range of radio command.

Ballistic missiles will probably be launched vertically, and will climb straight up in order to get out of the atmosphere as quickly as possible. At a preset altitude, the guidance system will turn the missile onto the required heading, with the required angle of climb. The missile is tracked continuously from the launching point, so that its position will be known as long as it is within radar range. Its instantaneous velocity can be determined either by establishing a range rate, or more accurately, by Doppler ranging. In the Doppler ranging system, a radio or radar signal is transmitted from the launching point. This signal is received and re-transmitted by the missile. By comparing the frequency of the original signal with that of the signal returned by the missile, it is possible to determine the missile speed with great accuracy.

There are a number of combinations of missile course, position, and speed that would result in a ballistic trajectory ending at the target.

But because the missile is constantly changing position at high velocity, no human computation can keep up with the problem. The known factors (position of the target and launching site, and preset heading of the missile) and the measured factors (velocity of the missile, and its position relative to the launching site) are fed into an electronic computer, which produces a continuous solution for the instantaneous values of the problem. When the computer determines that the missile's course, position, and velocity will result in the proper ballistic trajectory, the missile propulsion system is instantly and automatically shut down. The last stage of the missile then follows a ballistic trajectory, without further propulsion or guidance.

This system can be used effectively with missiles propelled by liquid fuel rockets, since the propulsion system can be shut down simply by stopping the fuel supply. If, like Polaris, the missile is propelled by a solid fuel rocket, the system cannot be used without modification. The Polaris guidance system will be described in a classified supplement to this volume.

B. Navigational Guidance Systems

10B1. Inertial guidance

Inertial guidance is so accurate that the submarine *Nautilus* on its first cruise under the polar ice cap, was able to use an inertial navigation system that was originally developed for use in long-range guided missiles.

With an inertial guidance system, a missile is able to navigate, from launching point to target, by means of a highly-refined form of dead reckoning. Dead reckoning is simply a process of estimating your position from information on: (a) previously known position; (b) course; (c) speed; and (d) time traveled. For example, assume that a ship's navigator determines his ship's position by astronomical observations with a sextant. The ship's position, and the time, are marked on the chart. Assume that the ship then travels for three hours on course 024, at a rate of 20 knots. From the known position on the chart, the navigator can draw a line 24° east of north, representing the ship's course. By measuring off on this line a distance representing 60 nautical miles (20 knots times 3 hours), the navigator can estimate the ship's new position by dead reckoning. If the ship changes course, the navigator will mark on the chart the point at which the change occurred, and draw a line from that point representing the new course.

A missile with inertial guidance navigates in a similar way, but with certain differences. It determines the distance it has traveled by multiplying speed by time. But it can not measure its speed directly if it is traveling at supersonic velocity outside the earth's atmosphere. However, it can use an accelerometer to measure its acceleration, and determine its speed by multiplying acceleration by time. To summarize:

velocity = acceleration x time
distance = velocity x time

The acceleration, of course, is not constant. It may vary due to uneven burning of the propellant. It will tend to increase as the missile rises into thinner air. Positive (forward) acceleration will become zero at burnout. If the missile is still rising at that time, it will have a negative acceleration because of gravity; if it is still in the atmosphere, it will have a negative acceleration because of air resistance. Acceleration will cause a constantly changing speed, and changing acceleration will change the rate at which the speed changes. If the missile is to determine accurately the distance it has traveled under these conditions, its computer circuits must perform a double integration. Integration is, in effect, the process of adding up all the instantaneous values of a changing quantity.

Both the accelerometers and the integrating circuits are fairly complex. But we can describe a simple, hypothetical system here that will be correct in basic principles. Assume that the accelerometer is a weight that can slide back and forth along the axis of the missile. The weight is mounted between two springs, which hold it in a neutral position when there is no acceleration. If there is a positive acceleration (tending to make the missile go faster), the weight will lag aft against the spring tension. If the acceleration stops, the weight will return to neutral position. If there is a negative acceleration

(tending to slow the missile down), the weight will move forward from its neutral position.

Now assume that the weight is connected to a potentiometer, in such a way that the potentiometer output is zero when the weight is at the neutral point. If the weight lags aft, the potentiometer output is a positive voltage; if the weight moves forward from the neutral point, the potentiometer output is a negative voltage. For an integrator, we can use a simple capacitor. During positive acceleration, the capacitor will gradually take on a positive charge from the potentiometer. If the acceleration then becomes zero, the charge on the capacitor will stop increasing, and will remain constant (indicating a constant speed). If the acceleration becomes negative, the charge on the capacitor will begin to drain off (indicating a decreasing speed). Thus the charge on the capacitor is the output of the first integrator.

If the first integrator output voltage is applied to the grid of a vacuum tube, it can be used to determine the rate at which current flows through the tube and into a second capacitor. The rate of current flow at any instant is proportional to the first integrator output, and therefore to missile speed at that instant. Thus the charge on the second capacitor is the output of the second integrator, and represents the total distance traveled up to any given instant.

Figure 10B1 is a block diagram of a simple inertial guidance system. This system has two channels—one for lateral and one for longitudinal acceleration. It uses both the direction channel and the distance channel to determine missile position. Each channel contains an accelerometer and circuit for double integration. The accelerometers detect missile velocity changes without the use of any reference outside the missile. The acceleration signals are fed to a computer which continuously produces an indication of both lateral and forward distance traveled by the missile. This is accomplished, in each channel, by integrating the missile acceleration signal to obtain a missile velocity signal. When this velocity signal is integrated, the result indicates the total distance that the missile has traveled.

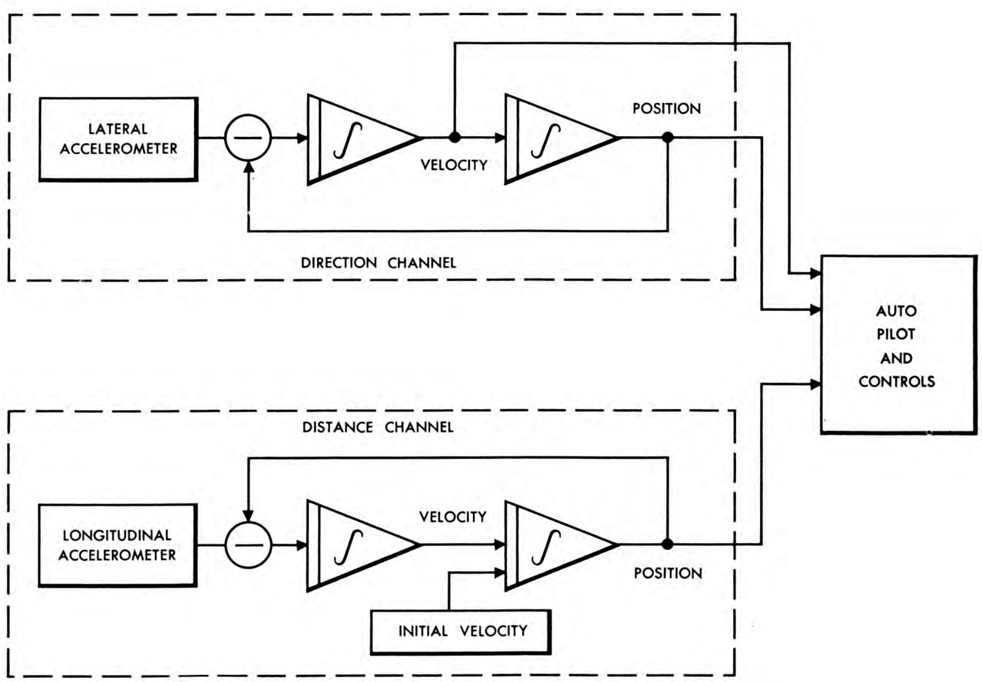

Figure 10B1.—Simple inertial guidance system.

DIRECTION CHANNEL. If the missile is on course, the output of the direction channel will be zero at all times. If the missile drifts off course, the output voltage of the second integrator will show, by its amplitude and polarity, the distance and direction the missile is off course. The output of the first integrator in the direction channel is the direction rate signal. Both of the integrator voltages are used by the autopilot to determine the amount and direction of control required to bring the missile back on course. Without these signals, the autopilot could only detect heading errors, not off-course conditions.

The accelerometer measures any force applied to the missile. The force of gravity is applied to the missile throughout its flight, and some types of accelerometer will be effected by it. In order to prevent a false output, the effect of gravity must be neutralized, so that only the true acceleration of the missile will be measured. This can be done in either of two ways. A part of the second integrator output can be fed back to the input of the first integrator, as in figure 10B1. Another system compensates for the effect of gravity by applying a fixed voltage bias to the output of the first integrator.

DISTANCE CHANNEL. The operation of the distance channel is much like that of the direction channel. The output magnitude of the first integrator indicates missile longitudinal velocity. The second integrator output voltage is proportional to the distance the missile has traveled. If the system does not start operating until after the launching phase is completed, the missile velocity at that time must be accounted for in the distance computation. A separate signal, representing initial velocity, must be fed to the input of the second integrator. It can then be combined with the output of the first integrator to indicate missile velocity at any given instant.

A comparison must be made between the distance the missile has traveled and the known distance between the launch point and the target. To do this, a voltage representing the distance to be traveled is set up as an initial condition just before missile launching. This preset voltage is combined, with opposite polarity, with the output of the second integrator. Thus the output of the distance channel decreases as the flight progresses. When the output falls to zero, the target has been reached.

There is one drawback to this system—the fact that for flights of several thousand miles, very large integrator output voltages would be required to get an accurate indication of distance traveled. The preset voltage that represents the target range would be equally large. In order to keep these voltages within reasonable limits, the voltage representing distance covered is continuously programmed during the flight by a suitable device such as a tape recorder. The programmed distance is compared to the measured distance, as represented by the computer output, in such a way that both are carried as reasonably small quantities.

Figure 10B2 shows another method of keeping signal voltages within reasonable limits by using a specified velocity signal. The specified velocity signal is combined with the first integrator output so that any voltage above or below the specified voltage is fed to the second integrator as an error signal. The output of the second integrator is then proportional to the missile error from the desired position on the course.

An inertial guidance system, such as the one just described, would be all that was needed if the missile flew straight and level at all times. But outside factors, as well as some

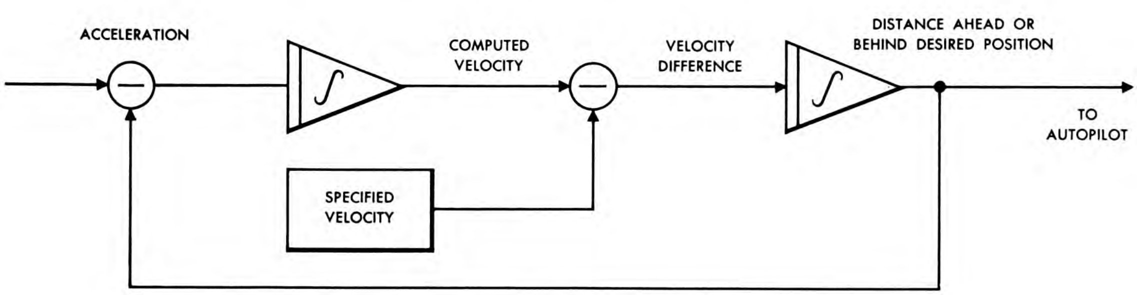

Figure 10B2.—Computer using specified velocity.

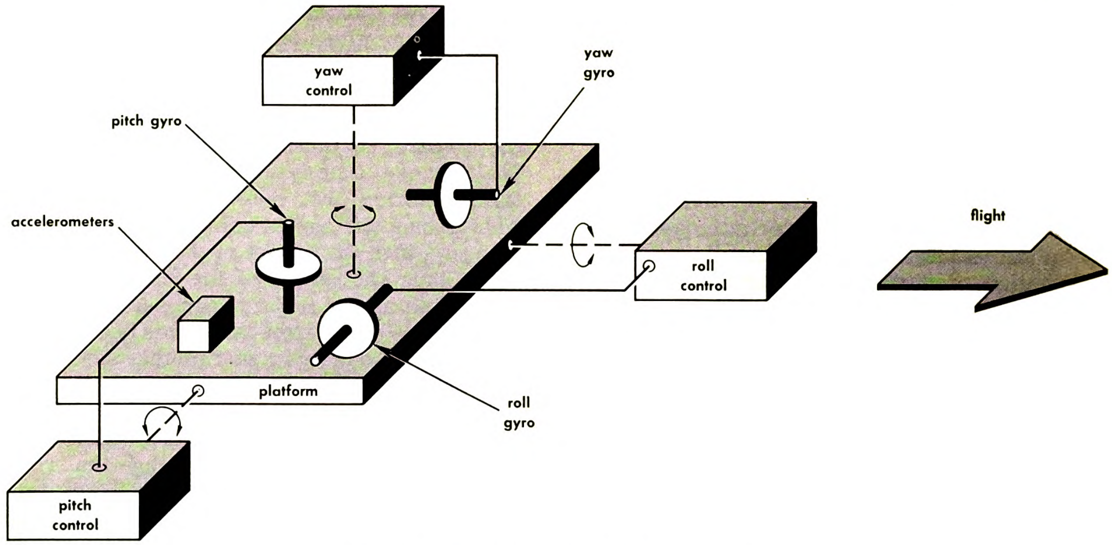

Figure 10B3.—Basic gyro-stabilized system.

errors introduced by the equipment itself, prevent straight level flights. Therefore a means for stabilization must be provided.

GYRO-STABILIZED SYSTEM. To get flight stability, the accelerometers must be mounted on a stabilized platform so that they will remain parallel to the earth and detect only accelerations relative to the earth's surface.

Figure 10B3 shows how accelerometers may be stabilized by mounting them on a gyro-controlled platform. The gyros are arranged to detect errors in the pitch, roll and yaw axes of the missile. Thus the output of the gyros will indicate any departure from stable flight. The error signal voltage is amplified and fed to a servo mechanism that corrects the platform position.

A previous chapter in this text explained how the gyro may drift because of bearing friction. Accuracy requires that compensation for gyro drift be provided. The compensation is obtained by adding an integrating loop to the system, as shown in figure 10B4.

Two loops are shown, one representing fast control and the other representing slow integration. Both loops use the gyro error voltage as a control signal. The fast loop functions rapidly to correct platform deviations from a level condition. The slow loop sums up the gyro drift error signals during the complete flight, because it cannot respond to rapid variations. During a normal flight, the random drift from a straight, level condition may be first to one side and then to the other. As a result, the sum of random drift over the entire

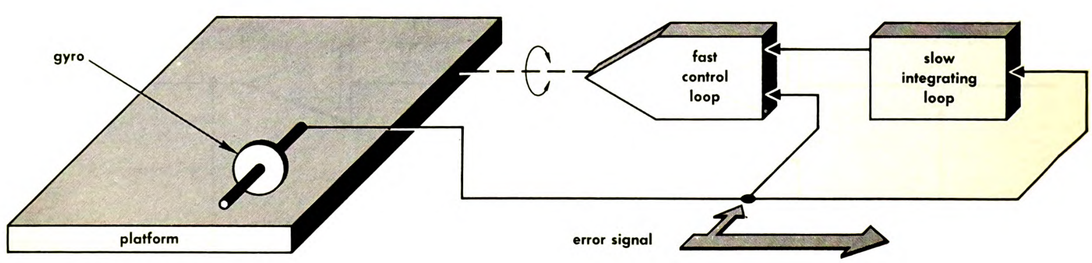

Figure 10B4.—Gyro-drift compensation.

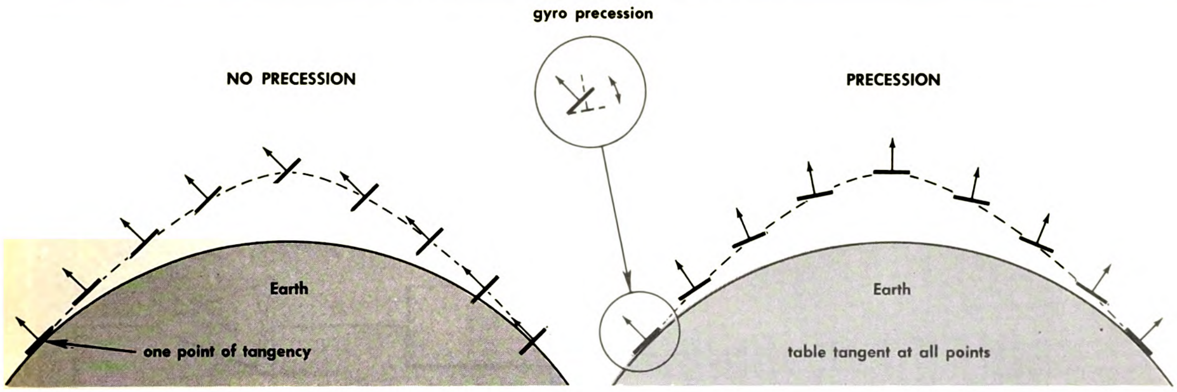

Figure 10B5.—Gyro precession for tangency with the earth.

flight will usually produce only a small total error.

PITCH CORRECTION FOR EARTH'S CURVATURE. The provision for keeping the platform level and preventing drift introduces a new problem. A normal missile trajectory is an elliptical path above the earth's surface. The gyro's characteristic of being fixed in space would mean that the gyro stabilized platform could be tangent to the earth's surface at only one place. In order to keep the platform tangent to the earth as the missile travels along its trajectory, the forward edge of the platform must be depressed at a rate proportional to the velocity of the missile around the earth. This keeps the platform level about the pitch axis with respect to the surface of the earth, as shown in figure 10B5.

Normally, gravity is used as a reference for slaving the gyro. But this is not done in an inertial guidance system. Instead, the platform is maintained in a level position by dividing, in the computer, the measured missile velocity by the distance between the missile and the center of the earth. The result of this division is a function of the angular velocity of the missile. The geometric relationship of the velocity factor is shown in figure 10B6. A study of the diagram will show that if the pitch angle of the platform is changed at the same angular velocity, the platform will remain tangent to the earth as the pitch axis changes.

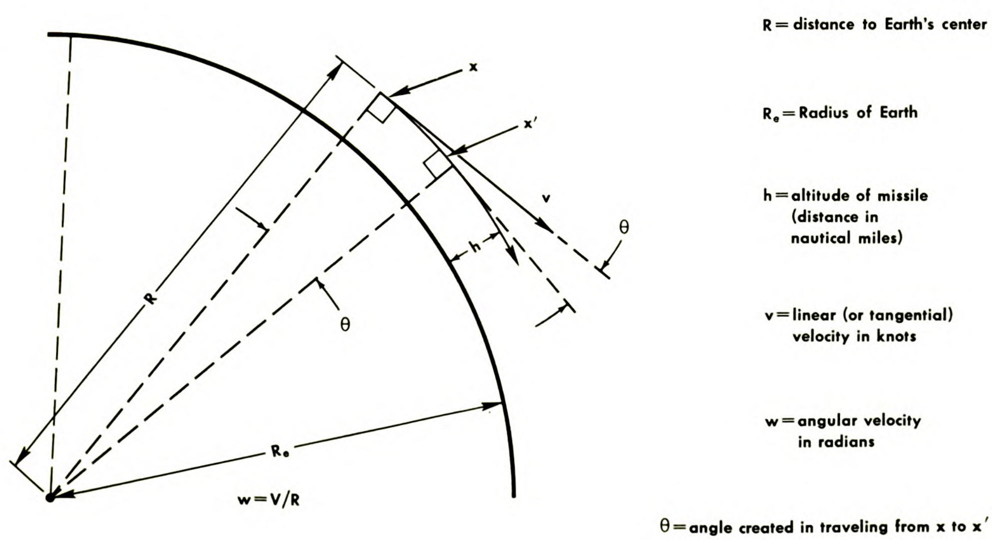

Figure 10B6.—Applying angular velocity to platform leveling.

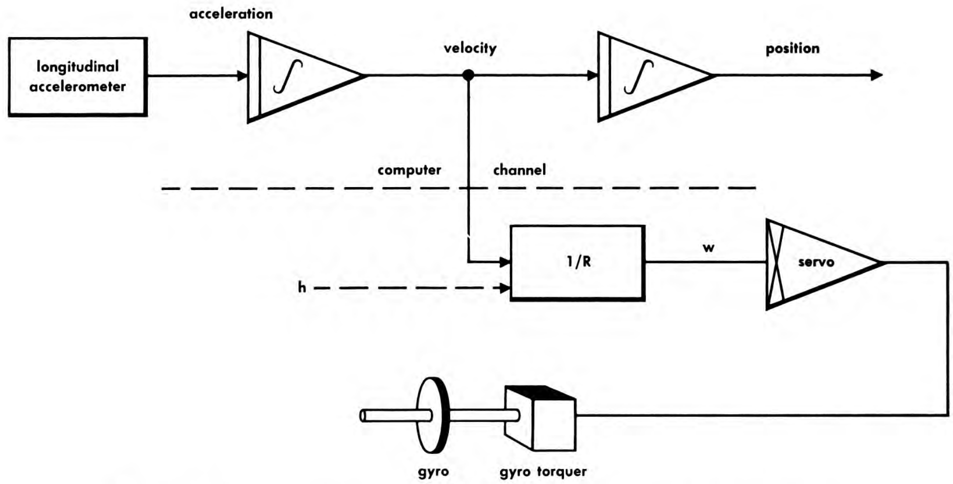

Figure 10B7.—Additions to the computer for angular velocity platform leveling.

The platform angle can be changed by precession of the pitch gyro. This precession is brought about by equipment in the computer section of the missile control system, as shown in figure 10B7.

In operation, the output of the first integrator, which is proportional to the missile velocity, is divided by the distance (R in fig. 10B6) to the center of the earth in order to give the missile angular velocity (W in fig. 10B6) in radians. The result is fed through the gyro torquer to precess the gyro at an identical angular rate.

It would be possible to make similar corrections for roll axis motion. The error in tangency would be small, however, because the missile moves such a small distance to either side of the desired course in comparison to the total length of the flight. Therefore, a simpler process is used to correct for roll. Instead of leveling a platform, a proportional bias voltage is applied to the accelerometer to correct its output signal.

Previous chapters of this text have shown that accelerometers, gyros, computers, and other sections of a complete control system can take many different forms. Individual devices may be mechanical, electromechanical, electronic, or a combination of these types.

10B2. Terminal inertial systems

As mentioned previously, the over-all guidance may be divided into three phases: launch, mid-course, and terminal. In this section, we will discuss terminal inertial guidance systems. This system uses a stabilized platform as a reference plane to carry the accelerometer sensors for a constant-dive-angle system. The function of any terminal guidance system is to place the missile directly on the target, rather than just in the general vicinity of the target. Thus, an accurate terminal guidance system can compensate for minor inadequacies in the mid-course guidance system.

The terminal guidance phase starts at a point in space known as the release point. This is where the mid-course guidance system is made inoperative, and the terminal guidance system takes over. There are two specific terminal inertial guidance systems. They are known as the constant-dive-angle system and the zero-lift system.

CONSTANT-DIVE ANGLE. A block diagram for a constant-dive-angle system is shown in figure 10B8. This equipment is able to compute the missile's position, during the dive to the target, with respect to the release point.

The output signals from the accelerometers are changed to velocity signals by the integrator. In the direction channel, signals then

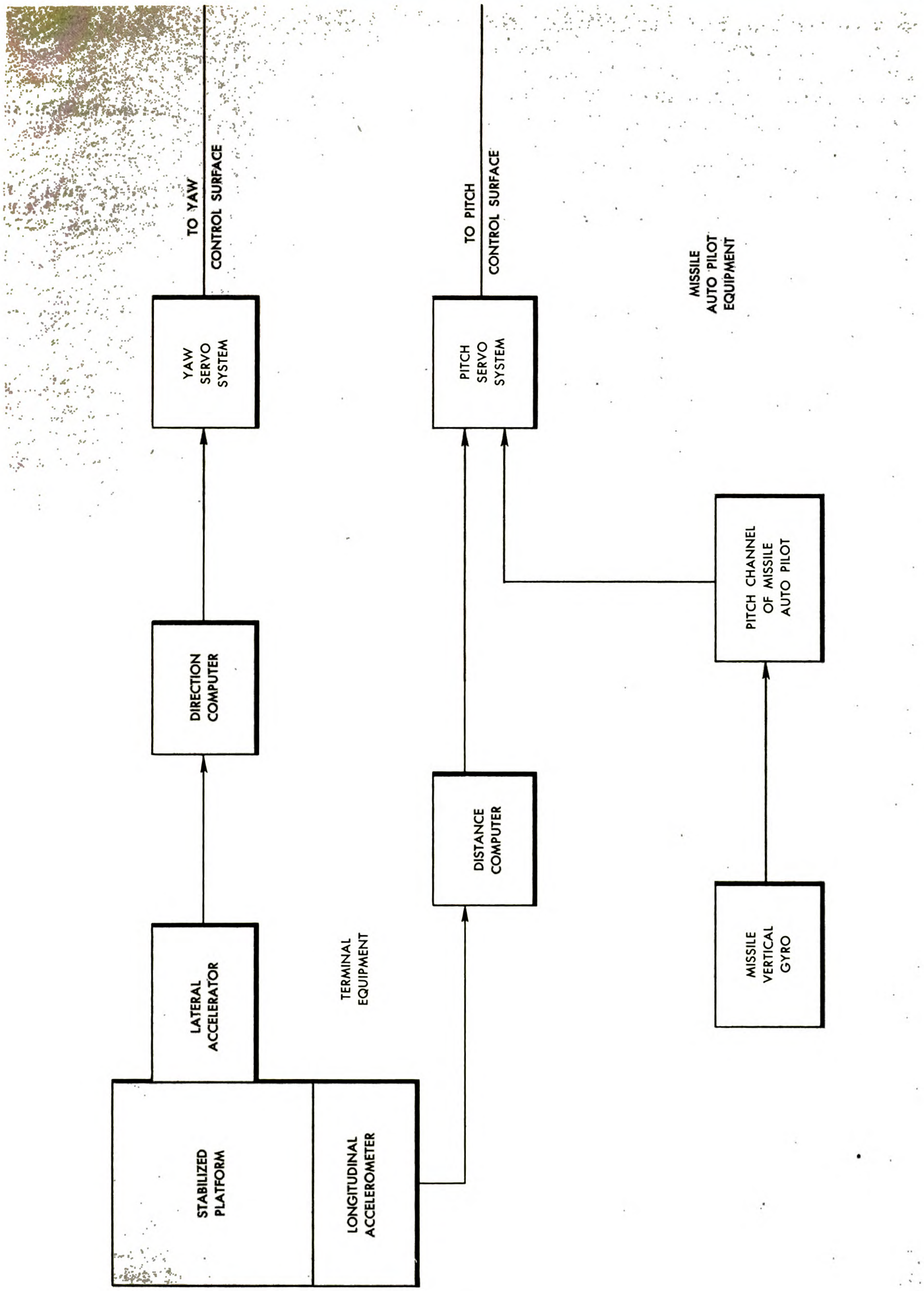

Figure 10B8.—Constant dive-angle system.

undergo a second integration to convert them into signals representing position. For a constant-dive-angle approach, the distance channel does not need position-error information. It therefore has only one integrator. The velocity signal is sent to the pitch servo system. If the velocity signal has the correct value, there will be no output from the computer to the pitch servo. If there is an error signal, it is fed to the pitch servo, which then corrects the dive angle.

VERTICAL-DIVE SYSTEM. The vertical-dive system is a variation of the constant-dive-angle system. The principle difference between the two is the location of the release point with respect to the target position. The constant-dive-angle system has the dive starting at a considerable lateral distance from the target. The system then sets up a constant-dive-angle which is maintained all the way to the target. The vertical-dive system release point is almost directly over the target, so that the missile can dive straight down.

The nose-over maneuver is accomplished by precessing the vertical gyro of the missile autopilot about its pitch axis. While there are a number of factors that determine the amount and rate of precession of the vertical gyro, the dive angle path to be followed is the primary factor in determining the number of degrees of vertical precession. The angle of incidence of the wings is another factor. This angle of incidence introduces a dive trajectory problem as shown in figure 10B9. Looking at the top drawing, we see that if the missile longitudinal axis were absolutely vertical, there would be some lift from the wings, which would pull the missile out of its vertical dive. In order to compensate for the lift of the wings, the controls are set for a slight over-control, so that the lift from the wings will keep the missile in a vertical dive.

When the pushover arc is completed, the missile is at the dive point. The autopilot is then cut off from the yaw and pitch servos, and has no further effect on the missile flight control surfaces.

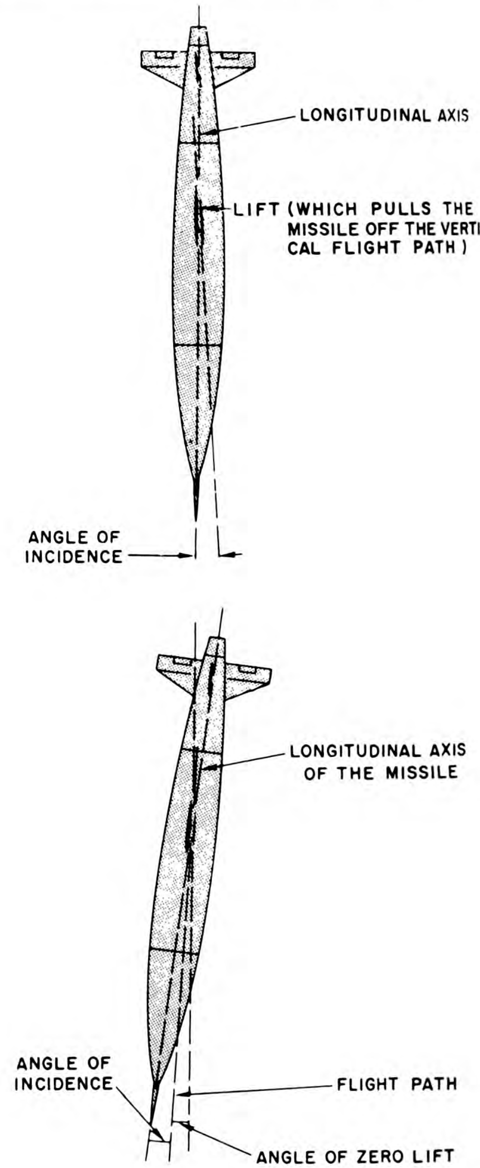

Figure 10B9.—Missile dive attitude.

ZERO-LIFT INERTIAL SYSTEM. The block diagram in figure 10B10 shows the zero-lift inertial system and the relation between it and the missile autopilot. This equipment has two functions. The first is to establish the flight path, which is programmed on tape. The programmed pulses drive a constant-speed motor, whose rotor drives the moving arm of a potentiometer. The second function is to keep the missile on the programmed path through the action of the accelerometer.

To accomplish the first function, the moving contact of the potentiometer must be moved from the ground end of the resistance

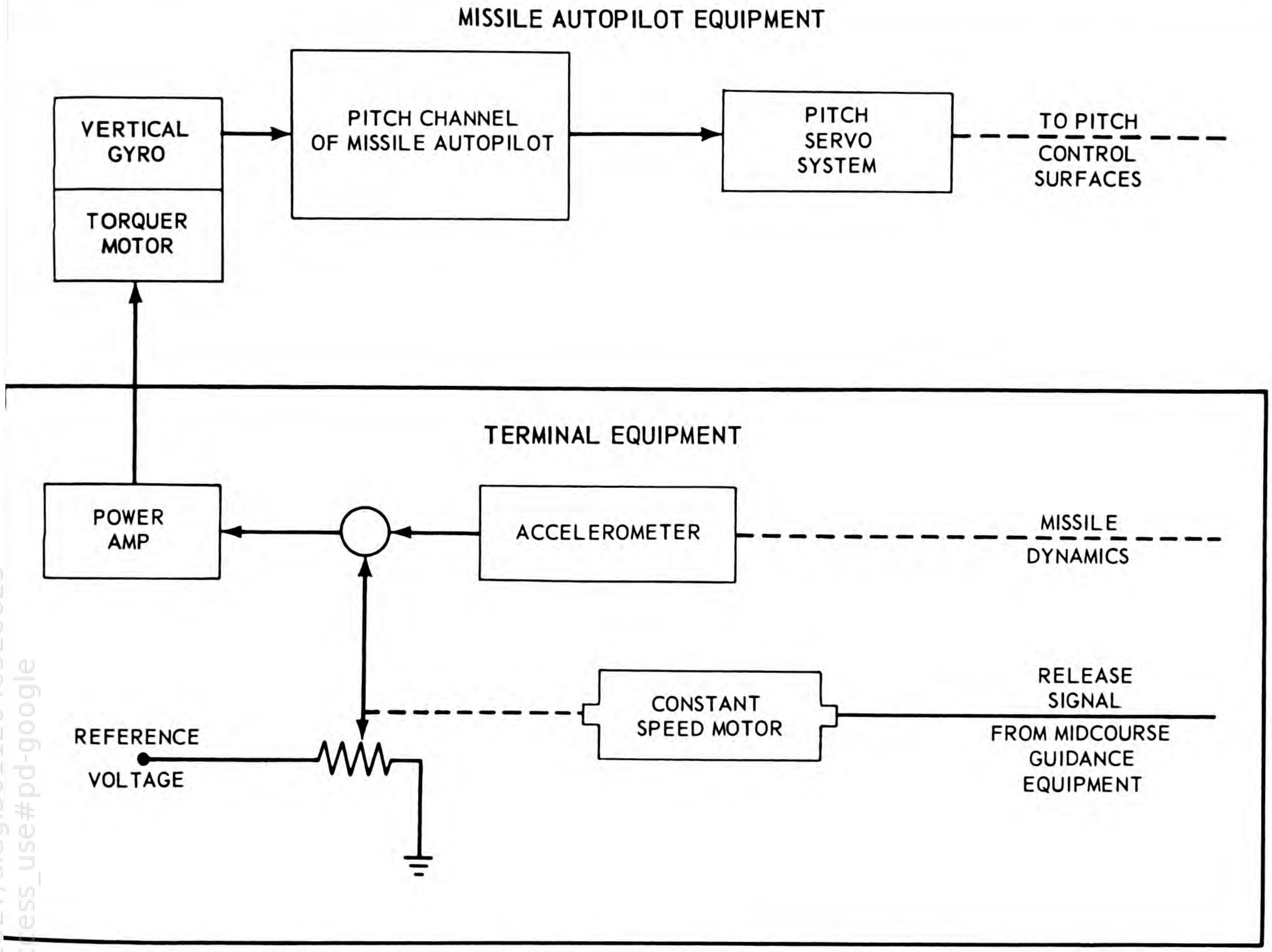

Figure 10B10.—Zero-lift inertial system.

strip to the other end at a constant rate of speed. Then, if the voltage between the moving arm and ground is plotted against time on a graph, the result will be a straight line. When this straight-line voltage is fed into a motor, the resultant displacement of the motor's rotor is an integration of the input voltage. Because the integral of a constant-slope line is a parabolic curve, the missile path from the release point to the target will be as shown in figure 10B11.

With a parabolic path as a reference for the pitch axis, the missile will try to follow that path. However, because of the wing angle and the engine thrust, the missile will actually fly a different path unless some compensation for these factors is made.

Compensation is provided by an accelerometer that is mounted so as to be sensitive to accelerations along the vertical axis of the missile. Therefore, if the wings exert a lifting force, the accelerometer senses the lift and originates a signal that corrects the vertical gyro precession. If the wings are exerting some lift due to a programmed signal, the signal from the accelerometer adds to the programmed signal in the mixer stage and causes the gyro to precess at a faster rate. If the missile noses over too far, there will be negative lift and the accelerometer sends a signal that subtracts from the programmed signal in the mixer, and slows up the precession rate of the gyro. Thus the missile flies the course shown in figure 10B11.

The actions just described provide the basis for the name of the system. The name zero-lift is used because the signal from

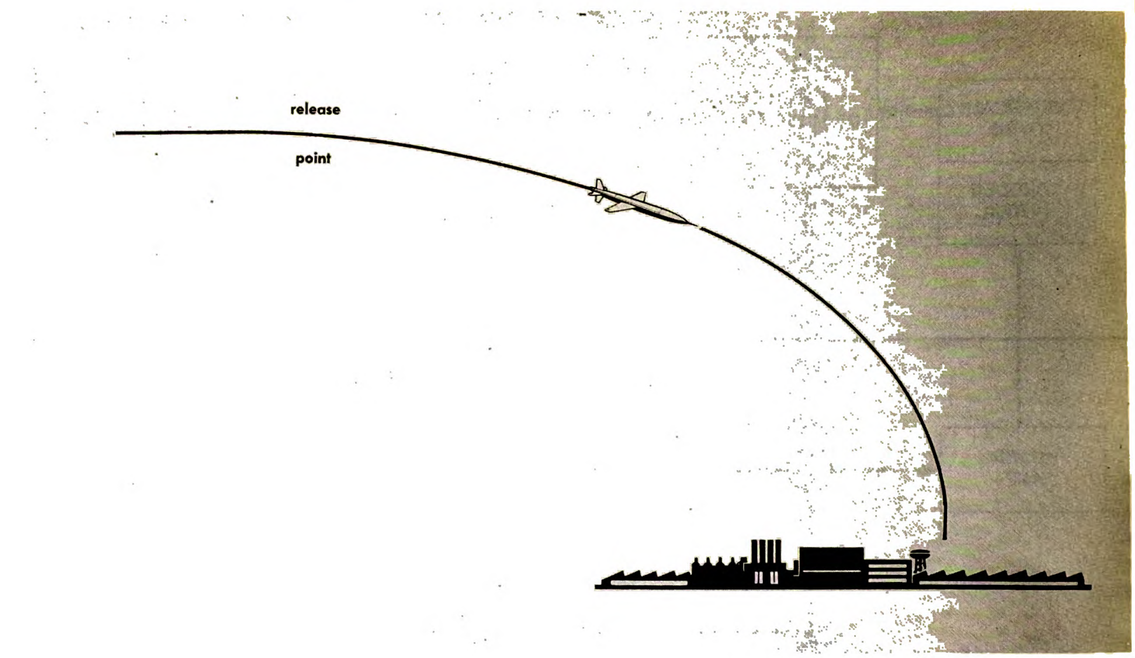

Figure 10B11.—Flight path of zero-lift inertial system.

the accelerometer compensates for any lift in the vertical axis of the missile.

10B3. Celestial-inertial system

Celestial navigation has been used for many years. The navigator uses a sextant to measure the angular elevation of two or more known stars or planets. From these measurements, a ship's position can be plotted.

The celestial-inertial navigation system uses a simplified approach to the problem; it uses an inertial system that is supervised by a series of fixes. One of these systems is known as STELLAR SUPERVISED INERTIAL AUTONAVIGATOR (SSIA); another is called AUTOMATIC CELESTIAL NAVIGATION (ACN).

In the stellar supervised autonavigator, periodic sights are taken on known planets or stars to check on gyro drift. As explained in another chapter, random gyro drift varies in both direction and magnitude. Because the slow-loop correction cannot predict the random drift of a gyro, we have an error that tends to increase with time. A probable error of one-half mile might be introduced during a flight of 45 minutes or so. Naturally, the error will increase with time.

One method that can be used to overcome random drift error involves the use of celestial sights. This is accomplished in much the same manner as a human navigator might check his position by sighting on the horizon and a known star. But the missile does not carry a human navigator; it must use a mechanical substitute. This device is an automatic sextant, so mounted that it can be moved in both elevation and azimuth. A combination mounting is shown in figure 10B12. The sextant is moved on two axes by motors. These motors are connected to the sextant-positioning system as shown in figure 10B13.

Operation of the system is programmed on a tape, which is pulled through a tape reader at a constant speed. The signal from the tape contains elevation and azimuth commands. These are fed to the proper control circuits. The tape is recorded before launching, and contains all the necessary position and rate data for the complete flight. To get accurate position checks, the sextant azimuth and

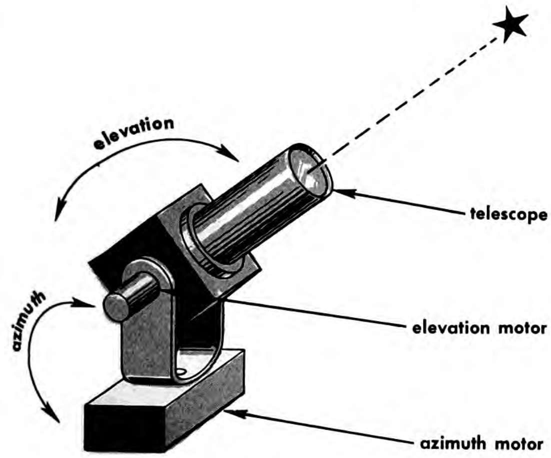

Figure 10B12.—Automatic sextant.

levation information must be read from the ape at the proper time. This is important ecause a star is at a particular angle with espect to a certain spot on earth only at a articular instant of time.

The sextant is aimed at a given star by in- ɔrmation taken from the tape, and then fol- ɔws the star from programmed information n the tape. The sextant position is varied by servo motors operating from the tape information. The automatic sextant output is fed into an error-detecting system, which is shown in block form in figure 10B14.

A scanner is used to detect errors in centering the star in the field of the sextant. The scanning system includes a light chopper or interrupter, and a phototube. If the star is not centered, an error signal is generated. This signal is then processed to give an indication of the sextant error.

As shown in figure 10B14, the stellar error-detection circuit has several output voltages that are proportional to the missile error in pitch, roll, and yaw. The light from the star, after passing through the scanner, falls on the light-sensitive cathode of the photocell. The cell output voltage is proportional to the light intensity. The output is fed to a selective amplifier that separates the signal from the noise. The amplifier output is then fed through a detector section to a resolver, which breaks down the signal into azimuth and elevation error signals.

The direction resolver has two outputs. One goes directly to the yaw comparator; the other goes to a second resolver section. The

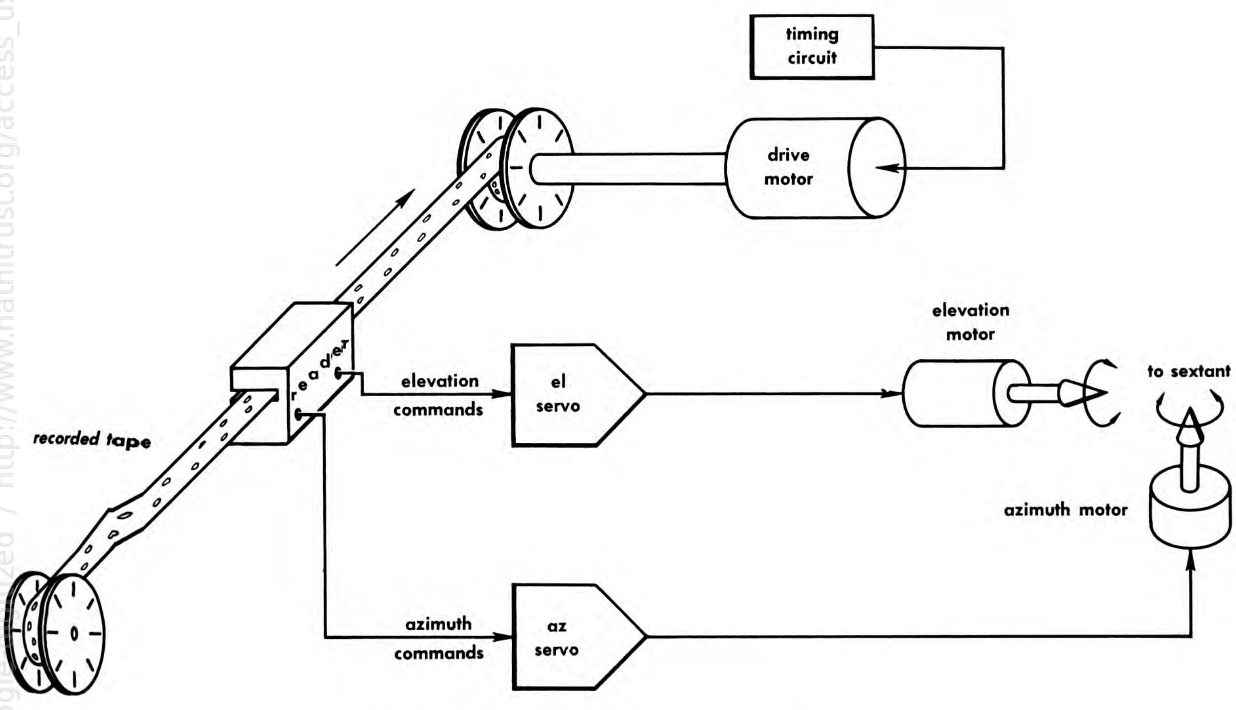

Figure 10B13.—Sextant-positioning system.

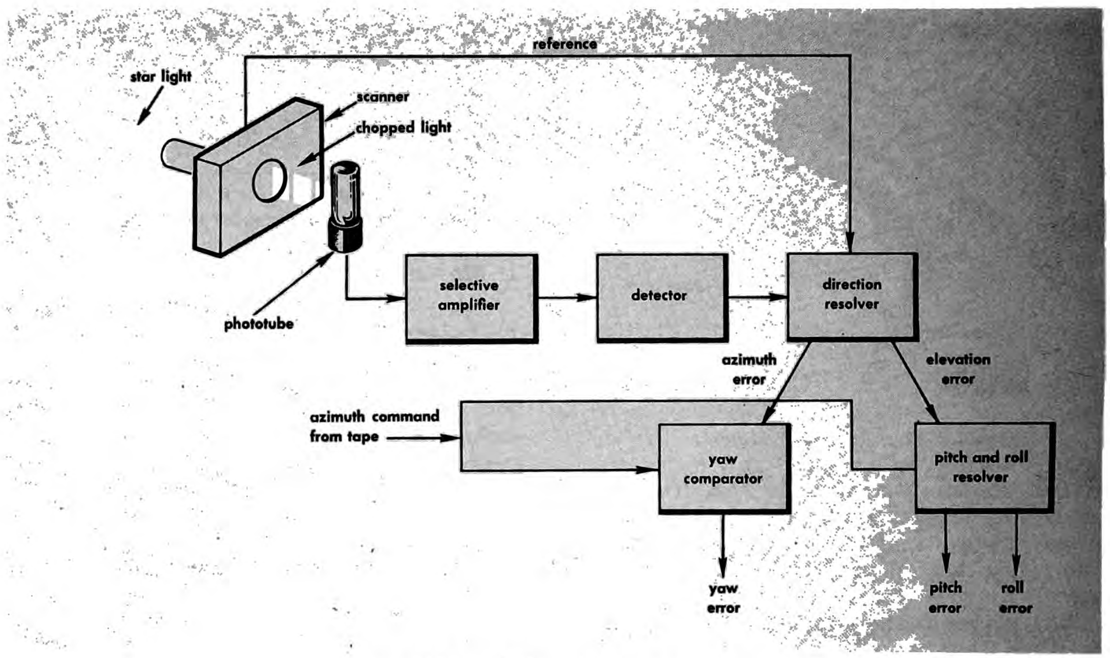

Figure 10B14.—Stellar error-detection circuit.

second resolver is controlled from the tape signals. The same signal that sets the sextant position sets the resolver for elevation error output. Unless the elevation signal is resolved in this manner, there is no way to determine the axis, pitch, or roll, in which the error exists.

If the sextant were raised and pointed directly forward along the missile heading, any elevation error signal from the sextant would be assumed to be an error about the pitch axis. If the sextant were pointed out the side, in a laterial direction, any elevation error would be a function of missile roll. Therefore a resolver is necessary to determine whether the error signal is caused by pitch, roll, or by a combination of the two.

An ideal way to use a star-sighting system is first to check a star whose line of position is parallel to the missile course, and to then check another whose line of position is at right angles to the missile course. The information from the first star would then be applied to the computer direction channel, and that from the second would go to the distance channel. These signals would then correct the gyros to a new position, and compensate for any gyro drift that might have occurred. The gyro outputs are fed to the autonavigator, which corrects the course. The pitch and yaw errors are corrected in the same manner.

10B4. Automatic celestial navigation

The most difficult problem to overcome in the system just described is gyro bearing friction. The problem may be solved by using a continuously supervised system. The automatic celestial navigation (ACN) system is continuously referenced by stellar fixes. This does not mean that there is no longer a necessity for inertial supervision; the inertial principle is still used by the autopilot between guidance commands.

The platform equipment for ACN requires one or more automatic sextants in addition to those already mentioned. Two sextants operate simultaneously to obtain a series of fixes, rather than a line of position. With fixes on two stars at the same time, there is less chance of error. It is possible that a standby sextant might be added to the equipment, so that it can zero in on the next star in the

avigation sequence without interfering with he fixes that are being made.

One disadvantage of the multiple sextant ystem is the need for a window big enough to iew a large area of the celestial sphere. Such window would need optical characteristics ıat would add greatly to its cost. In addition, ıe larger window area is more subject to amage by natural forces at high speeds.

LIGHT DISPERSION BY SHOCK WAVES. s light passes through any light-conductive ıaterial, a certain amount of refraction or ending, takes place. The higher the density f the material, the greater is the degree of ending. Rays of light are refracted when ıey pass obliquely through the shock waves ıat are generated by any missile traveling n air) at or above the speed of sound. This ffect may be severe enough to limit the use f celestial navigation to missiles operating t less than sonic speeds, or those operating ıt of the atmosphere. Figure 10B15 shows ıe effect of shock waves on optical systems.

NOISE FILTERS. In a practical applica-on, noise exists in the output of the velocity-ıeasuring component. The noise is in the ɔrm of short bursts, or peaks, of energy. It ıay be effectively removed by choosing com-onent values to give the proper time constant lelay) in the circuit. But a filter of this type s not suitable for use in removing noise of a ontinuous nature. If some steady error, due ɔ noise, is present in the signal that indicates velocity, the entire computer output will be in error. The elimination of errors caused by noise requires a circuit that will block noise error signals but pass other signals. A circuit with the desired characteristics is a high-pass filter that uniformly passes a-c of the higher frequencies, but blocks any signal of a lower frequency.

High-pass filters using inductive and capacitive components are easy to construct; but precision components are necessary to get sharp frequency characteristics, and this fact increases the cost considerably. To avoid costly components, a d-c amplifier with integrator feedback is used as a high-pass filter.

The integrator section is designed to respond slowly to an input signal. It may take as long as 10 minutes for the integrator signal to build up enough to cancel a steady amplifier input signal. Therefore, all voltages that vary at a faster rate will go through the circuit before the feedback becomes effective.

10B5. Terrestrial reference navigation

The search for accurate, foolproof missile guidance systems has turned up many possibilities. Some of those that seem the most fantastic are based on sound reasoning. The examples that follow fall into this category.

Several picture and mapmatching guidance systems have been suggested and tried. The purpose of an electronic unit of this type is to

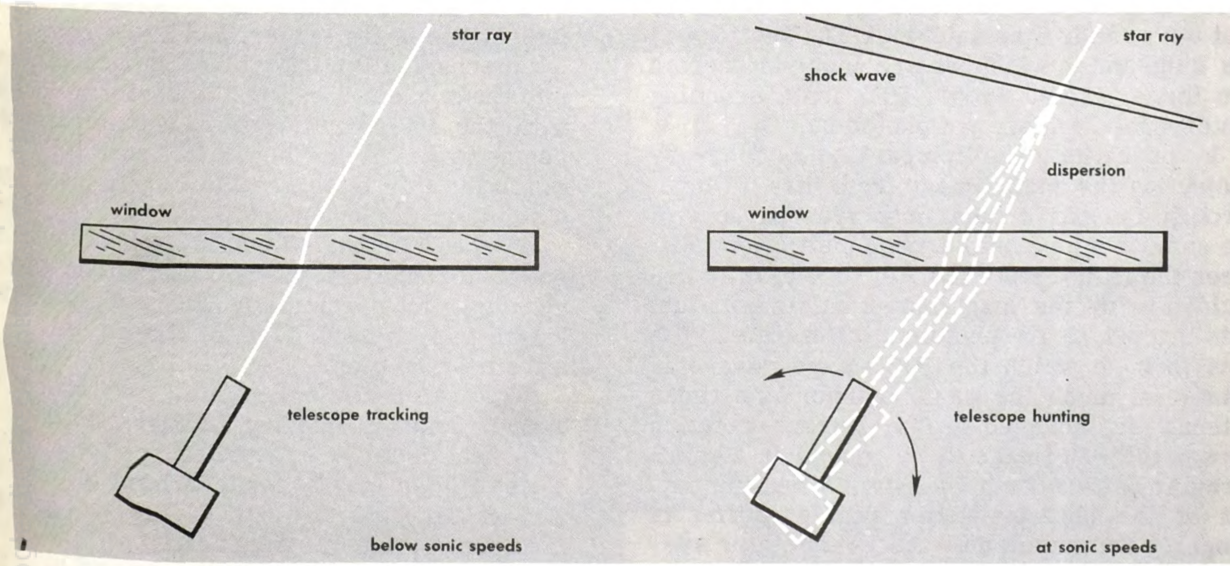

Figure 10B15.–Effect of high speeds on optical systems.

compare a photo or map carried in the missile with an image of the terrain the missile is flying over at that time.

The basic idea can be shown by using the common photograph as an example. If a photographic negative is placed over a positive (print) from that negative, the entire area will be black. If the positive were in the form of a transparency, the entire area would be opaque and no light would get through. If either the negative or the positive is moved slightly with respect to the other, light would show through where the two prints were out of register (not matched). If one transparency, say the negative, were in the form of a strip that was pulled through a frame or window by a servo motor, it would be possible to devise a control system that would automatically match the images. However, instead of a transparency for the positive image, the projected image of the terrain from a lens or radarscope would be used.

Daylight systems are ruled out because they would be seriously affected by clouds, fog, and smoke. The use of photographs of the actual course or target area would not be suitable for the reasons outlined above, and because such a system would be susceptible to countermeasures. On the other hand, a radar mapmatching system has greater effective range, and is not limited by conditions of visibility.

RADAR MAPMATCHING. Figure 10B16 shows a block diagram of a guidance system that uses radar mapmatching. The sections of the diagram in which we are most interested are those labeled radar, PPI, lens, scanning motor, map, holder, and phototube.

In operation, the comparison is made by projecting the radar image from the PPI tube, through a negative radar map transparency of the same region, onto a photomultiplier tube. When the image from the PPI tube exactly coincides with the map image, minimum light gets through to the photomultiplier tube. The lens through which the PPI image passes is rotated in much the same manner as a radar antenna is scanned. The mirror rotation causes the PPI image to be moved in a small circular pattern over the film. When the output of the photomultiplier tube amplifier is properly commutated by the commutator section, left-right and fore-aft information is obtained.

The pulses from the commutator are applied to d-c discriminators and integrators. Then, as shown in figure 10B16, the information is fed to two loops, lateral and longitudinal. The left-right information is fed to a servo amplifier which drives the film carriage laterally to keep the images matched. The position of the carriage is picked off as an error signal voltage for the missile control system. As the missile turns on its yaw axis, to correct the heading, the film carriage is moved and the error cancels out.

Fore-aft information is fed to the longitudinal servo loop that pulls the film through the holder at the correct speed to maintain a match between the film image and the PPI tube image. This means that the film speed must be proportional to the ground speed of the missile. It is possible to key the film to indicate the location of a change of course or to start the terminal dive action.

Errors can result from a difference in altitude between reconnaissance (radar mapping) and tracking (actual missile flight) runs because of slant range distortion and altitude-return delay.

It is necessary to have angular matching to within one degree before accurate left-right and fore-aft information can be obtained. Angular matching can be obtained by means of a magnetic auxiliary such as a compass. Matching is maintained by the azimuth loop of the system.

Two types of film holders can be used. The frame type is the larger, and more complicated mechanically. It switches separate frames into the scanning area and is easier to lock on with the system. However, a better method seems to be the one shown in figure 10B17, in which the film is scanned through a mask with a semicircular opening.

If the film strip used in this system is pulled through the viewer at a speed corresponding to the missile ground speed, its length will be about 1/20 of that required for a frame-type map.

The reference maps may be obtained by actual radar mapmaking flights over the terrain that is to be traversed by the missile. These flights may be made at high altitudes in almost any kind of weather. Another method involves the use of synthetic maps.

The synthetic maps are prepared by using maps of the area, aerial photos, and other

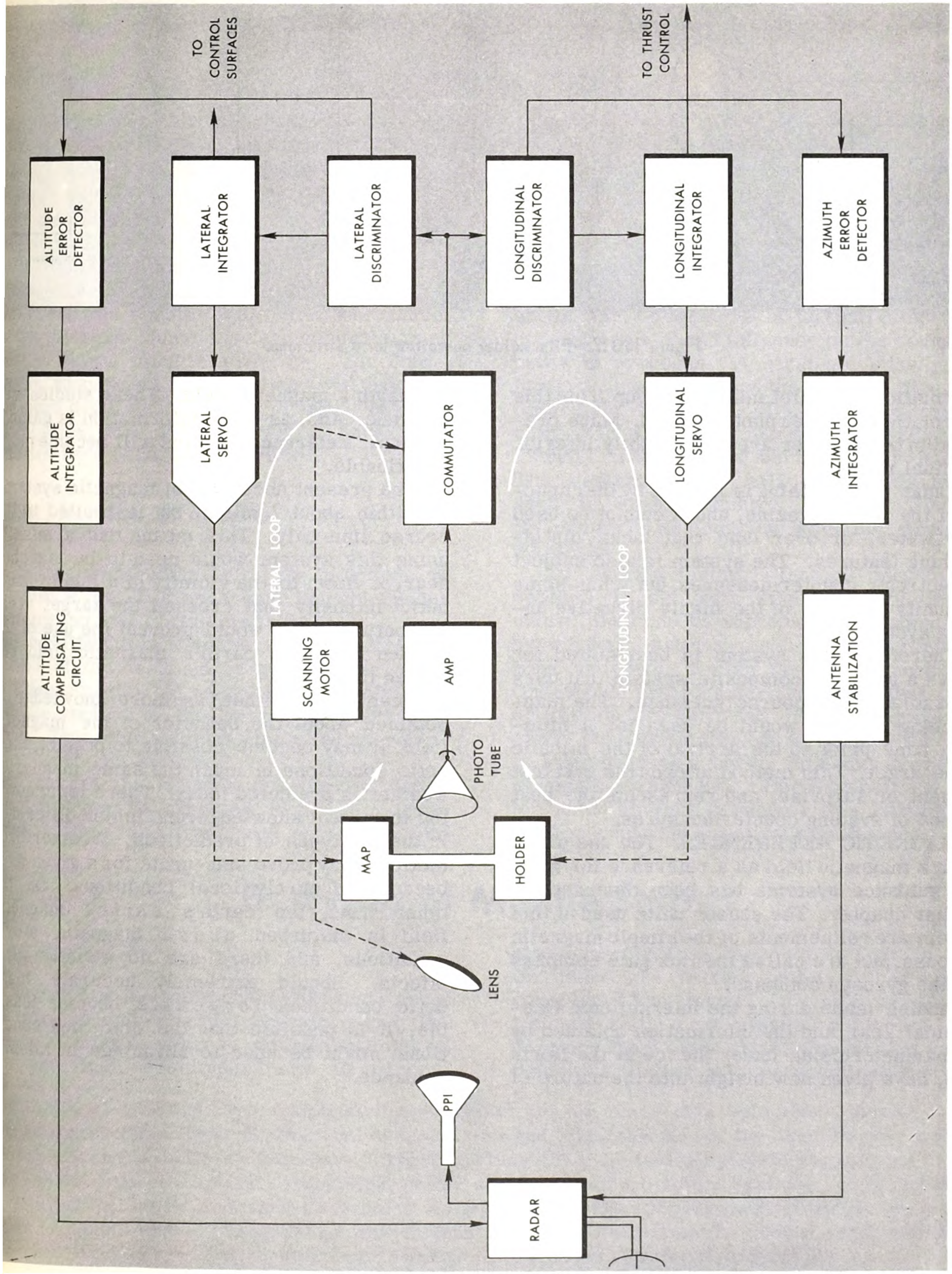

Figure 10B16.—Radar mapmatching systems.

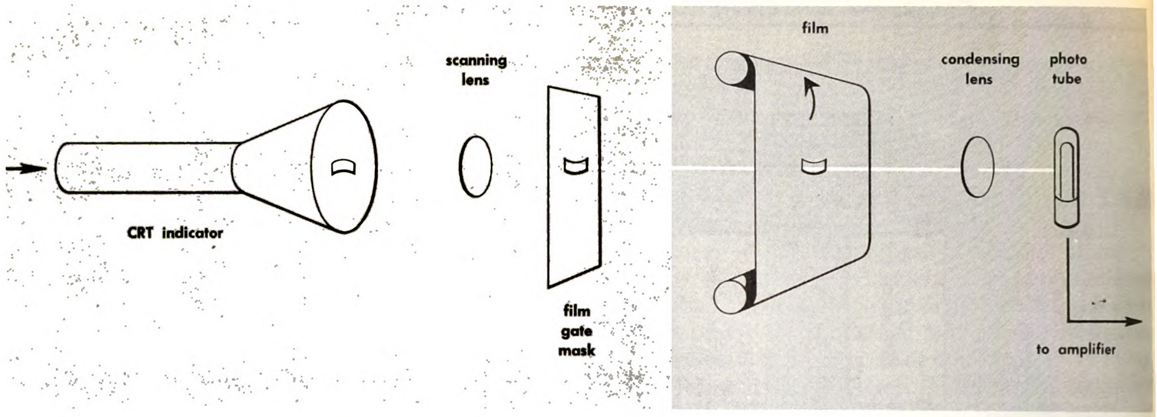

Figure 10B17.–Film holder operation for a strip map.

information. A relief map is built up from this information and then photographed. Maps prepared in this manner are only slightly inferior to actual maps.

Radar mapmatching is limited by the capacity of the film magazine, and it cannot be used over water, or over land that lacks distinguishing features. The system is also subject to electronic countermeasures, but it has some immunity because of the highly directive antenna system.

Therefore, this system is best suited for use as a part of a composite system that uses non-radiating midcourse guidance. The mapmatching system would be used for a minimum time prior to the arrival of the missile at the target. This method affords the greatest element of surprise, and represents the best method of evading countermeasures.

MAGNETIC REFERENCES. The use of the earth's magnetic field as a reference for missile guidance systems has been discussed in another chapter. The sensor units used in this system are refinements of the simple magnetic compass, and are called the flux gate compass and the gyrosyn compass.

Studies made during the International Geophysical Year, and the information obtained by submarine cruising under the ice at the North Pole, have given new insight into the nature of the earth's magnetic field. These studies will continue. And, as more information is gained, magnetic reference systems will become more practicable.

The present accuracy of magnetic systems is within about 7 miles, but is limited to the course line only. This means that a missile using this system would need to be launched near, or flown to, the vicinity of a line of magnetic intensity that crossed the target area. Magnetic storms would prevent the use of the system until the earth's magnetic field returned to normal.

Keep in mind that, as more knowledge is obtained about the behavior of the magnetic field, it may become possible to predict magnetic conditions in much the same manner as weather is predicted today. There is, according to present knowledge, one major difference in the two types of predictions. Weather predictions may prove inaccurate for a given area because of purely local conditions. On the other hand, the earth's entire magnetic field is disturbed under magnetic storm conditions, and there are no strictly local effects. Should extremely accurate magnetic conditions forecasts become feasible, it is possible that the disturbed conditions might be used to advantage in missile guidance.

CHAPTER 11

GUIDED MISSILE SHIPS AND SYSTEMS

A. Introduction

11A1. General

This chapter will describe the current guided missile ships and systems of the Navy. For reasons of national security, the material that can be published about the operational and technical characteristics of missiles, missile systems, and missile ships is necessarily limited. However, this chapter will orient the student to the missions, functions, and general nature of the Navy's missile program. The confidential supplement to this volume will describe in more detail those characteristics of missile ships and systems which have been omitted here because of security.

11A2. Mission of missile ships

Before proceeding with the missions of missile ships, it is necessary that the reader be familiar with certain definitions.

The MISSION of a ship is a BROAD STATEMENT of its designed purpose in the Navy. In a more restricted sense, the term MISSION can be applied to the component parts of a ship. Thus the term is also used in reference to missile systems.

Tasks of the mission specifically define what the ship is expected to do at a given time. There are two broad categories into which missions are sometimes divided—STRATEGIC and TACTICAL. These words are linked to STRATEGY and TACTICS. A full discussion of the meaning and significance of these terms could extend the length of this chapter. However, quick insight can be grasped by remembering that tactics is the art of battle, and that strategy is the art of war. Therefore, a tactical mission is one that has a direct influence on the course of battle in progress. A strategic mission[1] is far-reaching—it is one that has no direct or immediate influence. The job of providing close fire support to permit the advance of friendly troops would be tactical in nature. The destruction of ball bearing factories deep in enemy country, thereby affecting the enemy's war-making potential, would be strategic.

To explain further, tactical targets, as opposed to strategic ones, are fleeting in nature; they can be successfully attacked only by weapons that can reach them in minimum time and with a high degree of accuracy. One should not consider, however, that these definitions are hard-set. For example, consider the destruction of an enemy airfield. In one phase of a battle this may only have strategic significance. But the destruction of the same airfield in support of a landing operation would have tactical significance.

B. Types of Missile Ships

11B1. General

Because of the rapid changes brought about by many recent scientific breakthroughs, the design of missile ships or missile systems is not yet firm. Prototypes tend to become obsolescent before they can be put to use. But there are certain patterns that can be considered fundamental. At the time of writing this text, most missile ships are conversions from older ships. Conversion rather than construction is an economical approach

[1] STRATEGIC MISSION: a mission directed against one or more of a selected series of enemy targets with the purpose of progressive destruction and disintegration of the enemy's war-making capability and his will to make war. Targets include key manufacturing systems, sources of raw material, critical material, stockpiles, power systems, transportation systems, communication facilities, and other such target systems. As opposed to tactical operations, strategic operations are designed to have a long-range, rather than immediate, effect on the enemy and his military forces. (Dictionary of U. S. Military Terms for Joint Usage.--OpNavInst 3020.1B)

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to a guided missile Navy. In many ways it is a necessary approach, since as yet missiles cannot perform all the tasks that might be expected of them. There are still some jobs that a gun can do better than a missile. In addition to the conversions there are, in building and planning, ships designed from the keel up as missile ships.

11B2. Guided missile cruisers

In general, the mission of missile cruisers is to provide medium- or long-range AA defense, to bombard enemy shore installations, and to conduct combat operations against enemy surface craft.

Some of the tasks assigned to missile cruisers are: to provide effective AA defense of task forces, by means of missiles, at ranges greater than those obtainable with conventional guns; to provide close-in defense against enemy air attacks with AA guns; to provide defense against enemy surface attack; to control aircraft; and to bombard. Those cruisers equipped with assault missiles, such as Regulus, would be assigned additional tasks for the launching and control of these surface-to-surface missiles.

It is interesting to note that in addition to the above tasks, cruisers are being designed to include an ASW capability. This will enable them to provide defense against enemy subsurface attack, and thus permit a field of action much greater than that of older cruisers. Figure 11B1 indicates a possible task force formation of the future. Note that the cruisers have no need for direct ASW support, and that the force is spread out over many miles of ocean.

There are several classes of guided missile cruisers. First, there are the CAG (Terrier) conversions. Figure 11B2 is a picture of the *USS Canberra* (CAG-2). This class of ships is the result of conversion of World War II heavy cruisers. From outward appearances, the conversion consists of removing the after 8"/55 triple turret with all its accompanying equipment, and substituting two twin Terrier launchers and two Terrier guidance systems. However, the details of the conversion are more comprehensive than they might first appear. The reader will realize this upon completion of section "C" of this chapter, which describes the extent of the CAG (Terrier) weapons system.

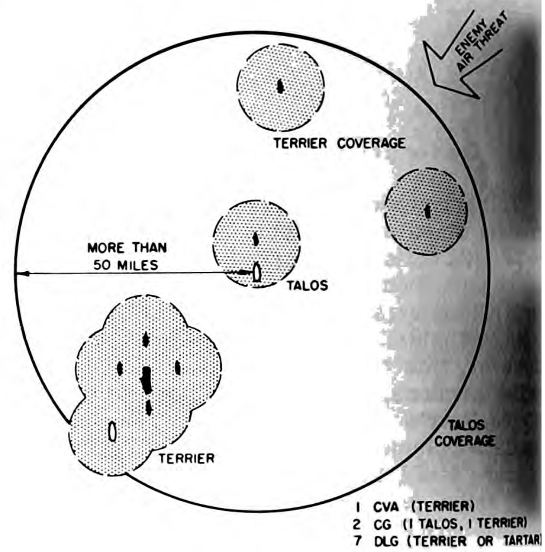

Figure 11B1.—A possible disposition of a missile-equipped carrier task force.

Figure 11B3 shows a second class of missile cruisers—the CLG (Terrier) class. These ships are conversions of World War II light cruisers. The armament of the CLG (Terrier) consists of the following:

1-twin Terrier launcher
2-missile guidance systems
2-6"/47 triple turrets
3-5"/38 twin mounts

A CLG (Terrier), converted to include fleet flag facilities, will have further modification of its gun batteries.

Of the CLG (Terrier) conversions, the USS *Providence, Springfield,* and *Topeka* will become the CLG's 6, 7, and 8, respectively.

Another class of guided missile cruiser is the CLG (Talos). For the purpose of this book, the only significant difference between the Terrier- and Talos-equipped CLG's is in the capabilities of the missiles themselves. The CLG (Talos) is converted from the same class of light cruiser, and the resulting armament is essentially the same as that described for the CLG (Terrier). In the CLG (Talos) class, there are the *USS Galveston, Little Rock,* and *Oklahoma City,* CLG's 3, 4, and 5, respectively.

Other cruisers, such as the *Macon, Helena, Toledo,* and *Los Angeles,* are currently equipped to stow, launch, and guide the Regulus I

Figure 11B2.—*USS Canberra* (CAG-2).

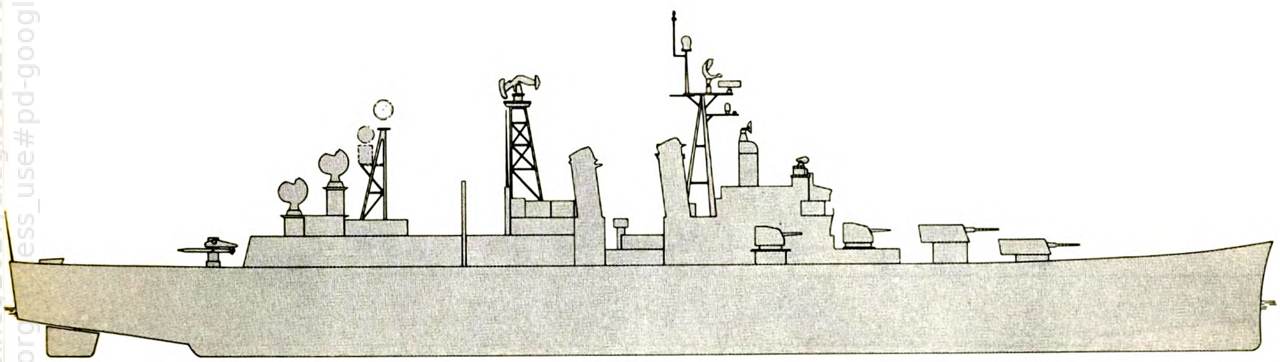

Figure 11B3.—The CLG (Terrier).

assault missile. Tactically, the assault missile's main target would be enemy land-based facilities; but the missile can also be directed against enemy surface craft. Figure 11B4 shows the *USS Helena* (CA-75) making preparations to fire a Regulus missile from her fantail launching position.

To complete the picture, there is the guided missile cruiser which has been designed from the keel up as a "double-ended" guided missile ship. Figure 11B5 is an artist's interpretation of the *USS Long Beach* (CGN-9), which will be armed with both long- and medium-range SAM's and the latest ASW armament (ASROC).

11B3. DD-type missile ships

Present planning provides for two families of destroyer types having a missile capability. The first of these is the guided missile destroyer (DDG). The DDG is similar to the conventional destroyer in displacement and other general characteristics. The second DD family is the guided missile frigate (DLG). The DLG is the big sister of the DDG, with longer endurance and better sea-keeping abilities.

The mission of the DDG is to screen task forces and convoys against enemy air, surface, and submarine threats. Figure 11B6 is

Figure 11B4.—Regulus I in readiness on *USS Helena* (CA-75).

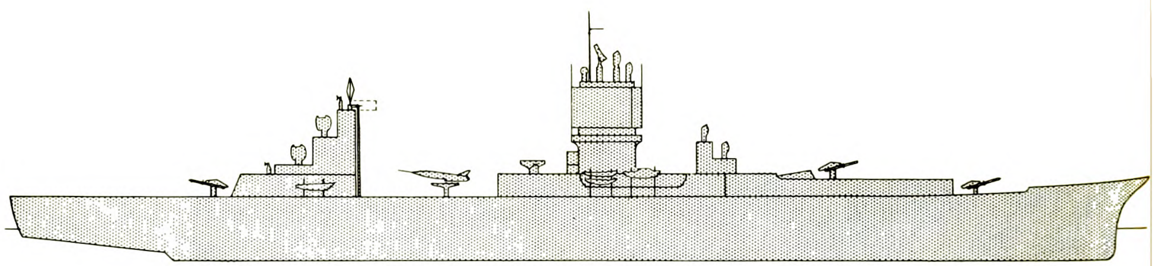

Figure 11B5.—*USS Long Beach* (CGN-9).

a picture of the *USS Gyatt* missile conversion, a prototype for the DDG classes to follow.

The primary mission of the DLG is to screen fast task forces. Figure 11B7 is an artist's interpretation of the DLG-16 class, an advanced design of an all-missile DD type. Some of the principal data about the DLG-16 class is as follows:

Missile battery:	2 twin Terrier launchers
	4 Terrier guidance systems
Gun battery:	2 3"/50 RF twin mounts
ASW:	ASROC and ASW torpedoes

The appearance of the DLG-16 class is exceptionally "clean," because the boiler uptakes are incorporated with the radar masts.

11B4. Guided missile submarines

The primary mission of the guided missile submarine is to deliver guided missile attacks against enemy shore installations. Its tasks include the launching and control of missiles and self-defense by means of underwater-launched weapons. Two families of guided missile submarines now seem to be emerging. The first are those designed to carry the Regulus, "air-breathing" variety of missiles. The second are submarines designed to carry the Polaris ballistic-type missile.

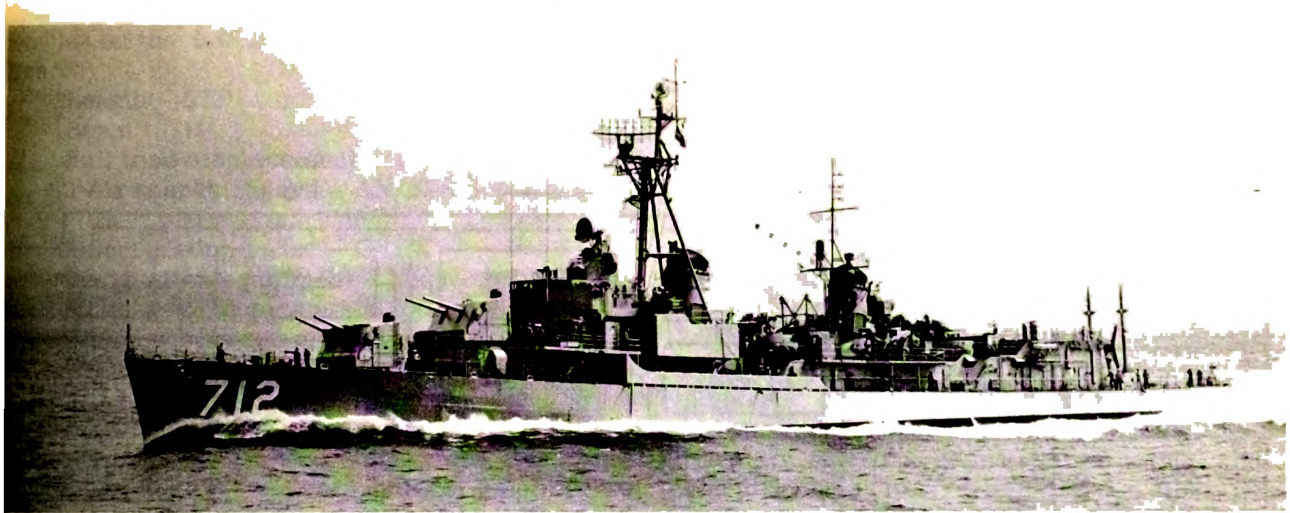

Figure 11B6.—*USS Gyatt* (DDG-712).

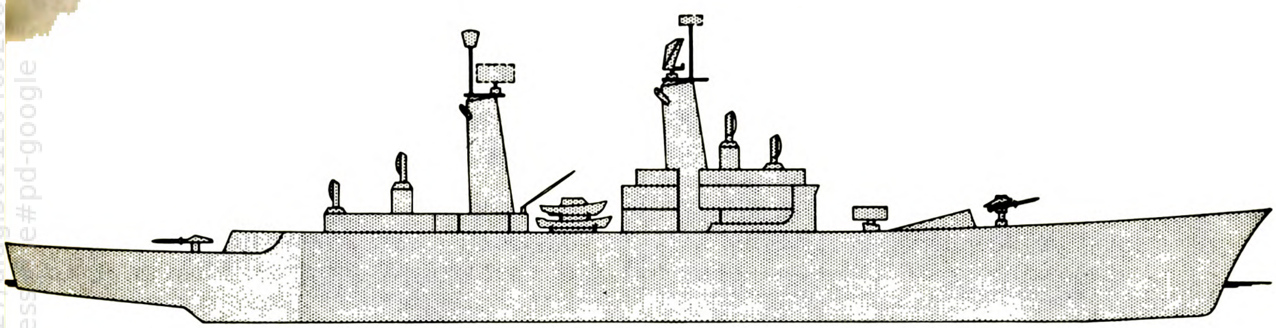

Figure 11B7.—The DLG-16 class.

1B5. Other missile ships

The Navy intends eventually to replace most f its conventional gunnery systems with mis- ile systems. Time and money appear to be the only quantities limiting the speed of this development. In the future, aircraft carriers, amphibious craft, and service craft will take their place in the missile Navy.

C. Surface Ship Missile Systems (CAG-Terrier)

1C1. General

This section will outline the fundamentals f a surface-to-air missile system as it might e found on a surface ship. Specifically, this ection will take up the Terrier SAM system s found on the CAG's *USS Boston* and *USS 'anberra*. The missile systems on these hips may be considered typical of a surface hip SAM system.

11C2. Organization of missile ships

The organization of missile ships is comparable to that of other ships with similar missions. Most of the equipment and personnel associated with the missiles are under the cognizance of the gunnery officer.

Figure 11C1 is the Gunnery Department organizational chart for the *USS Boston* (CAG-1).

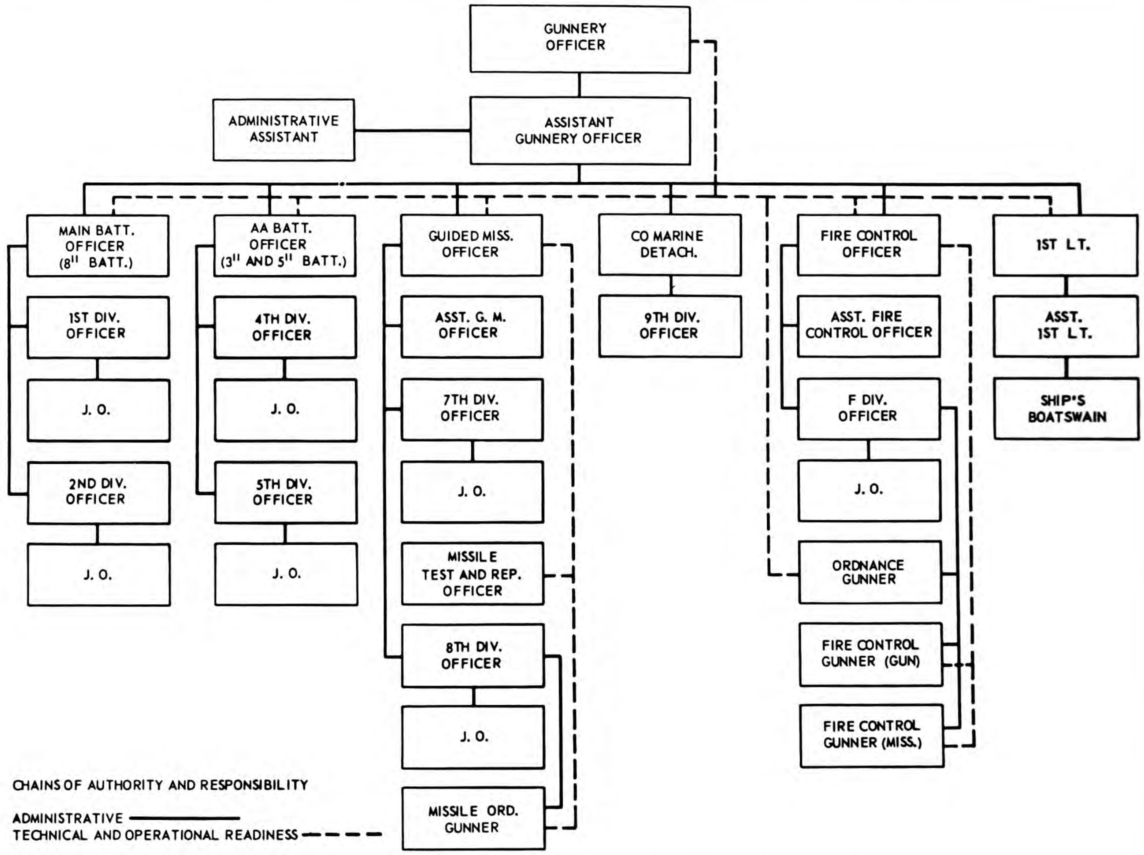

Figure 11C1.—Organization chart, Gunnery Department, *USS Boston* (CAG-1).

Men of the Guided Missileman rating are in the 7th and 8th divisions. These men are responsible for the operation and maintenance of the missile itself. Weapons control equipment of the missile system is under the cognizance of the fire control officer.

The missile system also gets an assist from Operations Department personnel, as Radarmen perform certain plotting and liaison functions in the weapons control system.

11C3. (CAG Terrier SAM) missile system

For the purpose of this text, we can consider the Terrier missile system of the guided missile cruisers *Boston* and *Canberra* as consisting of four major subsystems. These are:

- the missile,
- the ship,
- the weapons control system, and
- the missile stowage, loading, and launching systems.

THE MISSILE. As you will recall from the first part of this volume, the Terrier SAM is a medium-range beam rider, propelled by a solid-fuel sustainer rocket, and launched with a solid-fuel booster.

THE SHIP. The second major subsystem is the ship itself. The ship provides a launching platform. It also provides the basic services necessary for the maintenance and operation of the missile and the missile system. These basic services include electric power, communications, testing facilities, compressed air and nitrogen, logistics support, etc. The ship also provides early warning and other C.I.C. functions required for target acquisition.

Some pertinent data concerning the weapons complex on the *USS Boston* (CAG-1) is as follows:

Length - 673'
Beam - 71'
Full load displacement - 17,000 tons
3 Air search radars - AN/SPS 6c, 8, and 12
1 Designation radar - CXRX
Designation equipment - Mk 7
Missile computers - Mk 100
Other armament as indicated in figure 11C2.

Except for their missile directors, the *USS Boston* and the *USS Canberra* are essentially the same conversion. The directors on the *Boston* are of the "Mk 37" vintage, and are specially adapted for the Terrier with Mk 25 Mod 7 radar. The *Canberra* has a more advanced design, using the AN/SPQ-5 radar set.

WEAPONS CONTROL SYSTEM. This is the third major subsystem. It encompasses both the gun and missile fire control equipment. Because it is comparatively new, and unique in gunnery, the weapons control system will be described in some detail in this and the succeeding section.

Consider that an aircraft at 20,000 feet, traveling at 600 knots, will reach its bomb-release point more than 10,000 yards from its target. Consider, also, that this aircraft is traveling 20,000 yards a minute, and that the total problem may consist of two, three, or more aircraft. Finally, recall that in order to destroy an aircraft with a missile or a projectile it will be necessary to do all of the following BEFORE the target aircraft reaches its bomb-release point:

(1) Detect the target aircraft with radar
(2) Identify the target as "friend or foe"

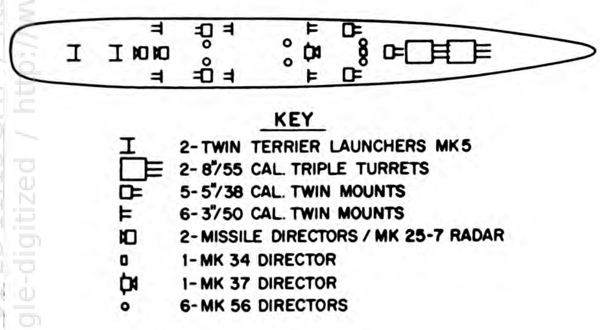

Figure 11C2.—CAG armament.

(3) Designate to a selected director until the target is acquired
(4) Obtain a solution with director's associated computer
(5) Assign weapons to the tracking director on a priority basis, and position these weapons in train and elevation
(6) Fire
(7) Wait until the projectile or missile reaches the point of impact with the target

The need for urgency, and the complexity of the AA problem, were the reasons for development of the complex weapons control system found on the CAG's and later ships. The CAG weapons control system was conceived to hold to a minimum the time required for acquisition of targets, and to permit simultaneous engagement of multiple targets. The large number of directors available on the CAG's makes it possible to direct fire against several targets simultaneously.

The weapons control system can be divided into fire control equipment and weapons direction equipment.

The FIRE CONTROL equipment supplies the basic intelligence and control functions for effective engagement of targets by the ship's weapons. Thus, with conventional gunnery, there is a need to compute gun orders. With missiles, there is a need to solve for launcher and in-flight guidance orders.

The WEAPONS DIRECTION EQUIPMENT provides the displays and controls required for the proper utilization of the ship's weapons. This utilization requires full evaluation of targets, assignment of missile (or gun) directors to the proper targets, proper selection of missiles and loading of launchers, tactical evaluation prior to firing, and, finally, continued evaluation to ascertain that targets are effectively encountered and that target priorities remain as first evaluated. Figure 11C3 is a picture of the *Boston's* weapons control station, which contains most of the weapons direction equipment.

MISSILE STOWAGE, LOADING, AND LAUNCHING SYSTEMS. In general, it can be said that the missile is handled in the same way that conventional ammunition and weapons are handled. However, certain missile characteristics modify the handling and stowage problem. The Terrier missile is heavy and unwieldy,

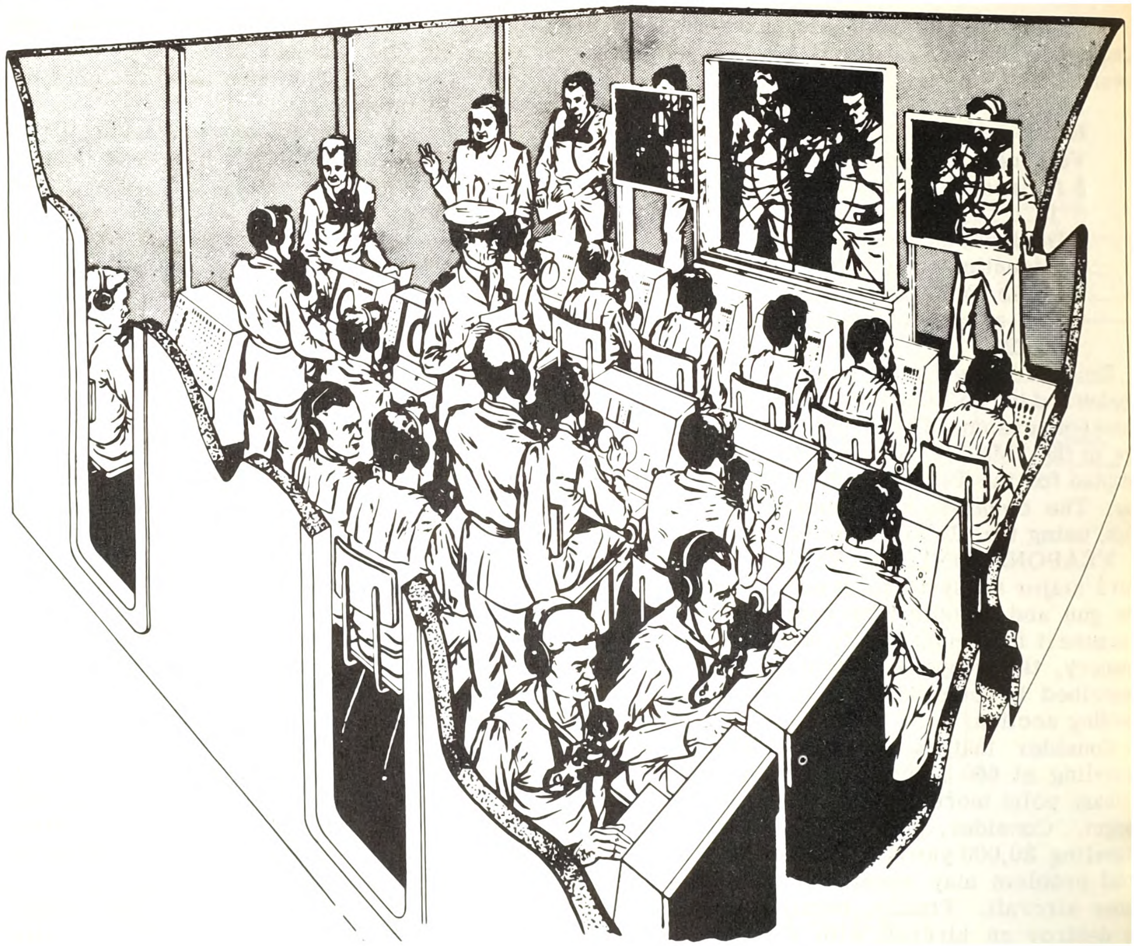

Figure 11C3.—Weapons control station.

since its length with booster is over 26 feet, and its weight is in the neighborhood of 2400 pounds. The electronic equipment, and the powder grains that make up the booster, require a controlled environment in order to maintain missile reliability. If subjected to cold, the boosters and sustainers become brittle and are more likely to fracture upon normal handling. A missile propellant that is cracked will burn faster than it normally should, becoming unreliable and perhaps extremely dangerous. Excessive heat and/or moisture will also have an adverse effect on the missile booster and sustainer propellants.

Each missile launcher has an associated magazine, ready service magazine, and wing-assembly area. The missiles are stored in a condition ready to be launched on short notice. Also, because of the rapidity with which the AA problem develops, provision is made for rapid loading of additional missiles and the jettisoning of malfunctions. With the exception of wing and fin assembly, the Terrier loading cycle is fully automatic.

A more detailed study of missile loading and launching systems will be included in the confidential supplement to this volume.

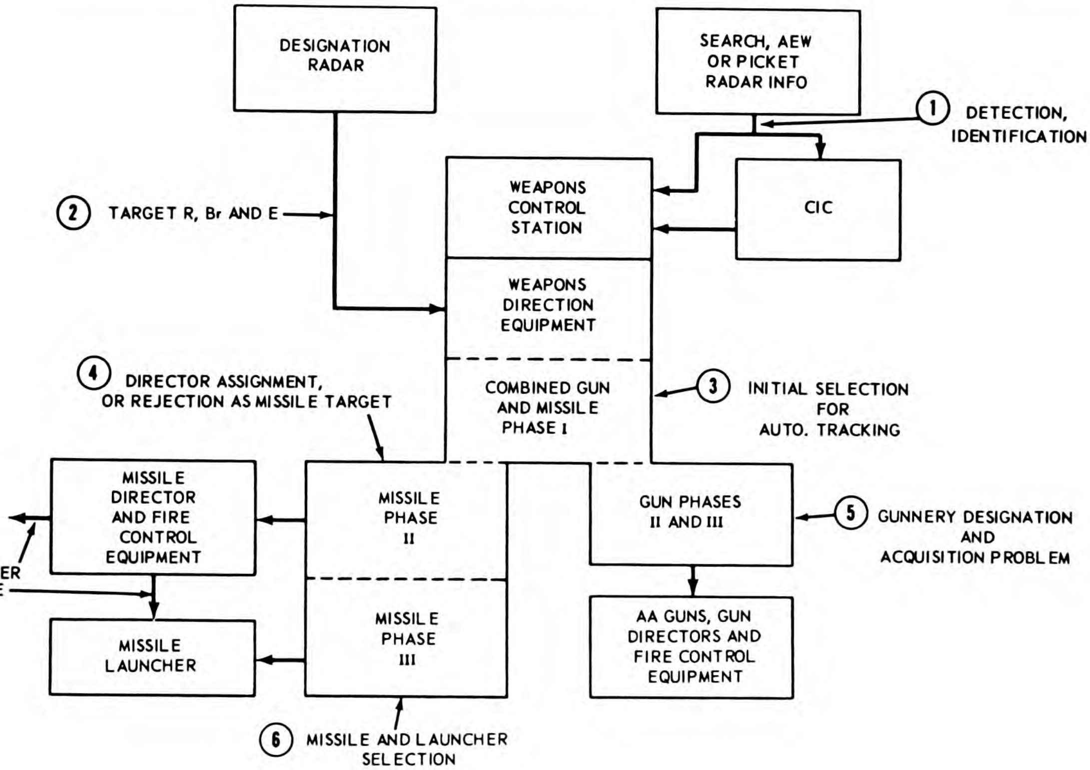

Figure 11C4.—Weapons control system (CAG - Terrier).

11C4. The AA problem

Figure 11C4 is a simplified block diagram that will help the reader to understand the functioning of the CAG (Terrier) weapons system as it concerns the AA problem.

DETECTION AND IDENTIFICATION. A target is detected by the ship's air search radar, by an AEW system, or perhaps by another ship acting as a picket (item 1, fig. 11C4). This target information is presented to CIC and the weapons control station in a conventional manner. The target is interrogated, plotted, and assigned a designation if not found to be a friendly aircraft.

TRACKING, EVALUATION, AND DIRECTOR ASSIGNMENT. This is the phase of the AA problem in which the sophistication of the CAG (Terrier) weapons control system becomes apparent. In addition to the conventional search and fire control radar normally found on Navy ships, the CAG has a designation radar installed as part of the weapons control system. The designation radar is a hemispherical scan radar, and it provides a continuous 360° HORIZON TO A GIVEN ELEVATION radar scan. Thus, the designation radar will supply range, bearing, and elevation of all targets within its range (item 2, fig. 11C4). All targets within the scope of the hemispherical scan radar are made available as inputs to the automatic tracking (TWS: track-while-scan system) feature of the weapons control system. Automatic tracking is necessary because of the requirement for speed, and because the number of targets may exceed the number of directors available, or the capability of human tracking. The CAG (Terrier) weapons control system is able to retain all target information in a ready-to-use form, for transmission to directors as rapidly as they are able to take successive targets.

Too, because of the limited time available, provision is made within the weapons control system for as much automatic evaluation (as opposed to human operation) and director assigning features as is possible. Thus an

aircraft attacking so as to be the most serious threat will automatically be given priority in director assignment.

WEAPONS CONTROL SYSTEM PHASES. Within the weapons control system are three successive phases of actions and equipments, as follows:

PHASE I—This is a combined phase I for gun and missile use, whereby targets are selected by the phase I equipment operators for automatic tracking. These phase I operators, aided by what is presented on their radar scopes and by the information received from CIC, then institute the automatic features of the TWS system. To summarize, phase I equipment provides for display, detection, initial selection, and tracking of targets (item 3, fig. 11C4).

PHASE II—This and succeeding phases will be discussed only insofar as they concern the missile problem. Parallel capabilities for target acquisition are provided for the gunnery problem (item 5, fig. 11C4). Phase II equipment for missilery provides for evaluation and assignment to a particular missile director, or for rejection as a missile target (item 4, fig. 11C4). If the target is rejected for missilery at this point (or at any other time), designation to a gunnery director must be considered. (The phase II equipment for gunnery will function automatically to assign to a gun director for acquisition any target that meets the priority requirements.) Duplication of effort is prevented by the fact that targets are normally engaged with missiles long before their priority dictates serious consideration by the gunnery assignment equipment.

To sum up what is done in phase II of the missile problem, the phase II equipment operators select and assign priorities to missile targets; they then assign the targets, in order of "threat", to the missile directors for acquisition.

PHASE III—The function of the phase III equipment is to receive and display all the comprehensive information necessary to select launchers and successfully fire the appropriate missiles against the selected targets (item 6, fig. 11C4). Information such as unclear areas, launcher availability, maximum and minimum missile capabilities, present and advance target position, etc. are available to the phase III equipment operators.

FIRE CONTROL. A director, having acquired the target designated by the weapons direction equipment, will, together with its computer, complete a solution. The solution is in the form of missile launcher orders and missile guidance orders (item 7, fig. 11C4).

The AA problem is completed when the target is destroyed, or when a director is released because of change in target priorities.

11C5. Missile logistics

Missile logistics is the problem of keeping the operating forces supplied with a stockpile of missiles and spare parts. Initially, missile components are shipped in sections from the manufacturers to storage depots located throughout the continental United States and at its advanced bases. Each of the sections that make up the missile is packaged in a reusable metal container. The containers are sealed, and contain desicant in order to provide an environment least likely to cause unreliability in the component. When necessary to supply the operating forces with a missile, it is the depot's responsibility to test, assemble, and transfer a complete missile in the form required by the recipient, A missile, being extremely complex and of large unit size and value, requires more care in transport and handling than a conventional round of ammunition does. For this reason, all handling equipment and shipping containers are designed to realize maximum missile reliability.

Once aboard the CAG, the missiles are again fully tested to ensure reliability. Missiles must either pass the rigid tests or be repaired. When any missile component fails in test, it is replaced with a spare and the rejected part is shipped back to a depot for complete overhaul. The CAG is equipped to make minor repairs and component substitutions, but not to make extensive overhauls. All the steps in missile manufacture, storage, handling, and testing are for maximum missile reliability.

Missile ships are equipped to receive replacement missiles both while in port and while under way. Transfer at sea is usually conducted by use of the burtoning method.[2]

[2]The burtoning method of transfer is one of the types of rig used to transfer material between ships while under way at sea. Burtoning requires each ship to maintain tension (with a winch) on the load being transferred between them.

D. Submarine Missile Systems

11D1. General

The Regulus missile can be considered a typical vehicle when speaking of submarine missile systems. Regulus, as you will recall, is a surface-to-surface tactical missile capable of carrying a high-yield war head. Polaris is another member of the Navy's submarine-launched surface-to-surface missile family. Though Polaris is a ballistic missile, certain functions of the Polaris missile system are similar to those of Regulus systems.

11D2. SSG (Regulus) missile system

The SSG (Regulus) missile system is somewhat less complex than the Terrier system described in section 11C. There are four major subsystems that must be considered to make up the guided missile submarine SSM system. These are: the missile; missile guidance equipment; the submarine; and missile stowage and launching systems.

Figure 11D1 is an inboard profile view of one of the latest SSG's, the nuclear-propelled SSGN-594 class.

The Regulus missile is a turbojet-powered pilotless aircraft. Guidance for this type of missile can be provided by any of several means, such as radio command, radar control, inertial guidance, and programmed flight, or by a combination of these methods. The type of guidance used depends on such things as desired accuracy, cost, simplicity, reliability, and probable countermeasures. Guidance selection, although it has a direct bearing on the design and operation of the missile system, is beyond the scope of this chapter. This chapter will deal primarily with the fundamentals of the submarine missile system that are common to all guidance techniques.

The third subsystem, the submarine itself, provides a launching platform, basic services, fuel, and other logistic support functions. Also included on the submarine are a navigational system, and missile fire control equipment.

The launching of missiles towards targets miles away can be compared to a very long range gunfire problem. The submarine will usually have no direct observation of the target, or of a known geographical reference. But the position of the guiding craft must be fixed with extreme accuracy. Location, heading, ground speed, and other reference data, all have an effect on the CEP[3] of the missile.

The SINS system (ships inertial navigation system) is presently the most sophisticated of the navigational systems now installed on missile submarines. The heart of SINS is an inertial guidance package based on the principles of inertial guidance explained in preceding chapters. Included within SINS are numerous gyros and accelerometers whose function it is to generate the submarine's position and speed, and to establish true north and a vertical reference. SINS, then, acts like a dead reckoning computer/analyzer whose

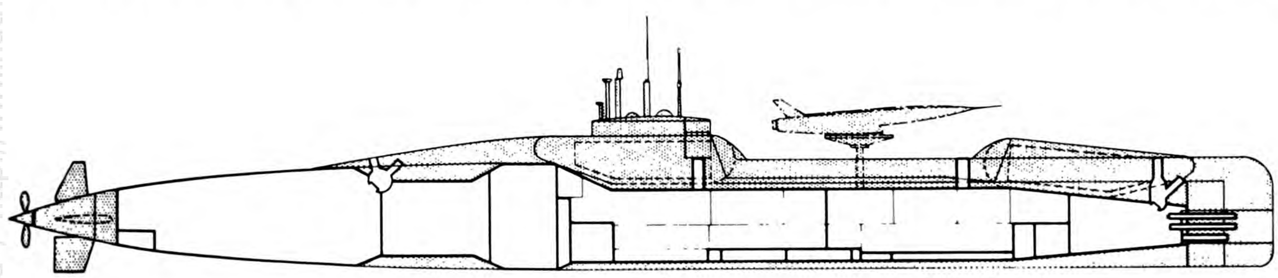

Figure 11D1.–SSGN-594 class.

[3]CEP—an abbreviation for "circular probable error" or "circular error in probability." This terminology denotes the accuracy of a weapon. Though having a deeper mathematical significance, it is defined as a circle within which a single weapon has a 50% chance of landing, or expressed differently, one CEP is a radius of a circular area within which 50% of all weapons used will hit.

function it is to provide continuous and extremely accurate navigational and reference data. It also has the ability to weigh, analyze, and make corrections to its dead reckoning solution based on optical and electronic navigational inputs.

In addition to the navigational system, a fire control system is included on the submarine. The function of the fire control system is to transfer reference information to the missile, and to control and monitor the missile during preflight checks.

The last subsystem to be considered is for MISSILE STOWAGE AND LAUNCHING. Regulus missiles are stowed in watertight hangars such as the one shown in figure 11D2. Pictured is the *USS Tunney* (SSG-282), one of the first U. S. Navy submarines altered for a missile capability.

Referring back to figure 11D1, you can see that in the most modern missile submarines, the missile hangars are faired into the submarine's structure. Thus the submarine is more streamlined, to permit higher submerged speeds.

When launching a Regulus missile, the procedure is for the submarine to surface, ram the missile to its launching position, make the final preparations for flight (final preflight checks and wing unfold), and fire. Once

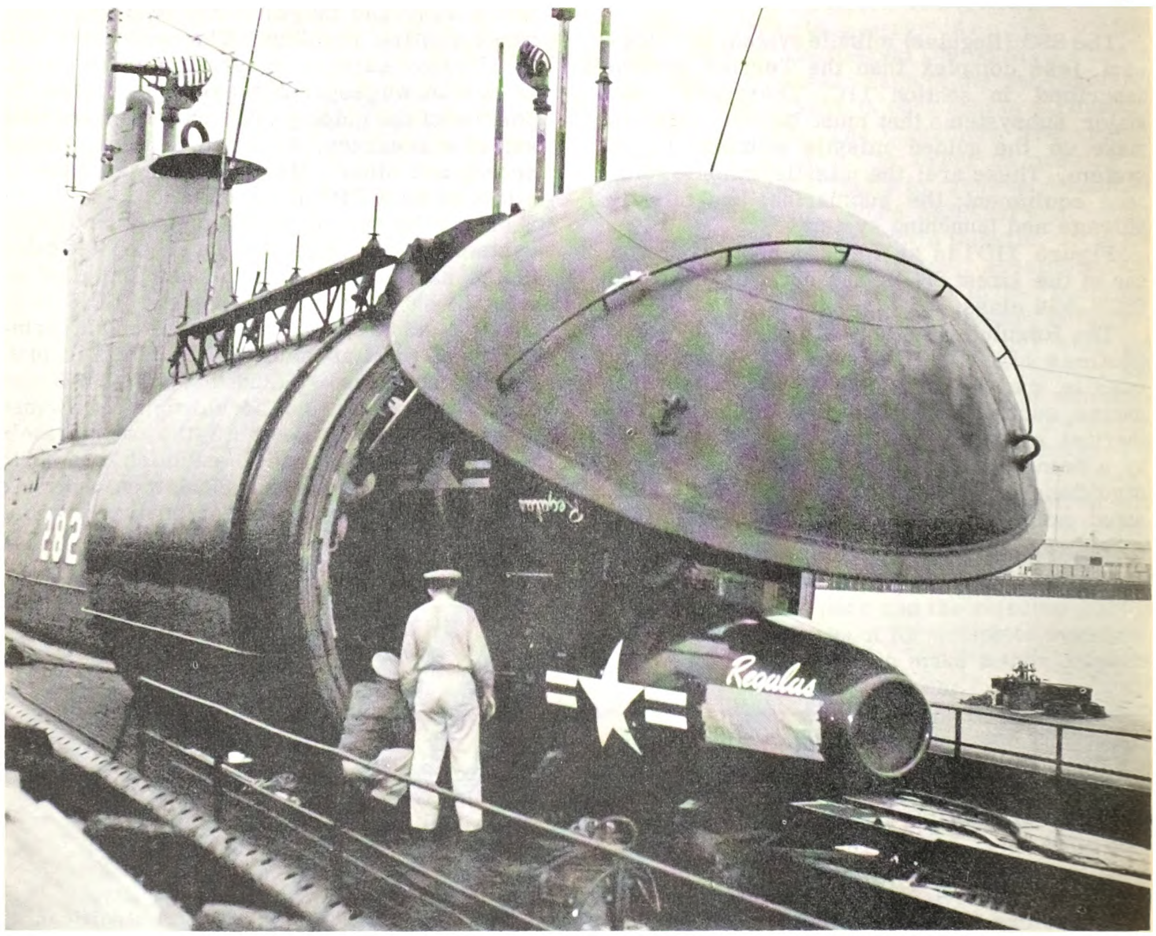

Figure 11D2.—Missile stowage on *USS Tunney* (SSG-282).

the missile is airborne, the submarine may again submerge and conduct any necessary guidance functions while submerged. Well-trained SSG crews can limit the time on the surface to minutes.

11D3. The surface-to-surface problem

TARGET CONSIDERATIONS. Because of the high unit value of submarine-launched SSM missiles, certain factors must be considered, such as the importance of the target to the enemy, and target nature, vulnerability, size, and location. With strategic targets, these factors are evaluated well in advance of the mission. Tactical targets require faster military decisions. Both planning estimates, however, are usually accomplished on a much higher planning level than the launching ship.

FLIGHT PLANNING. In addition to the target considerations, additional planning must be given to the flight plan of the missile. Regulus missiles, because they are turbojet-powered, fly most efficiently at high altitudes. Thus, whereas the missile would be most likely to remain undetected at very low altitudes, the range to the target may prohibit such employment. Intelligence and the immediate tactical situation also play an important part in missile planning.

ASSISTED GUIDANCE. This system permits the submarine to launch its missile at a relatively long distance from the target. One or more additional submarines, provided with the necessary guidance equipment, are deployed closer to the target or near known landmarks. Thus a second submarine may furnish accurate guidance during the final phase of the missile's flight, while remaining submerged and thus less likely to be detected. Figure 11D3 depicts a hypothetical case in which an electronically guided surface-to-surface missile is launched by a submarine at a location remote from the target; terminal guidance is provided by two other submarines, one controlling in azimuth and the other in range for maximum accuracy.

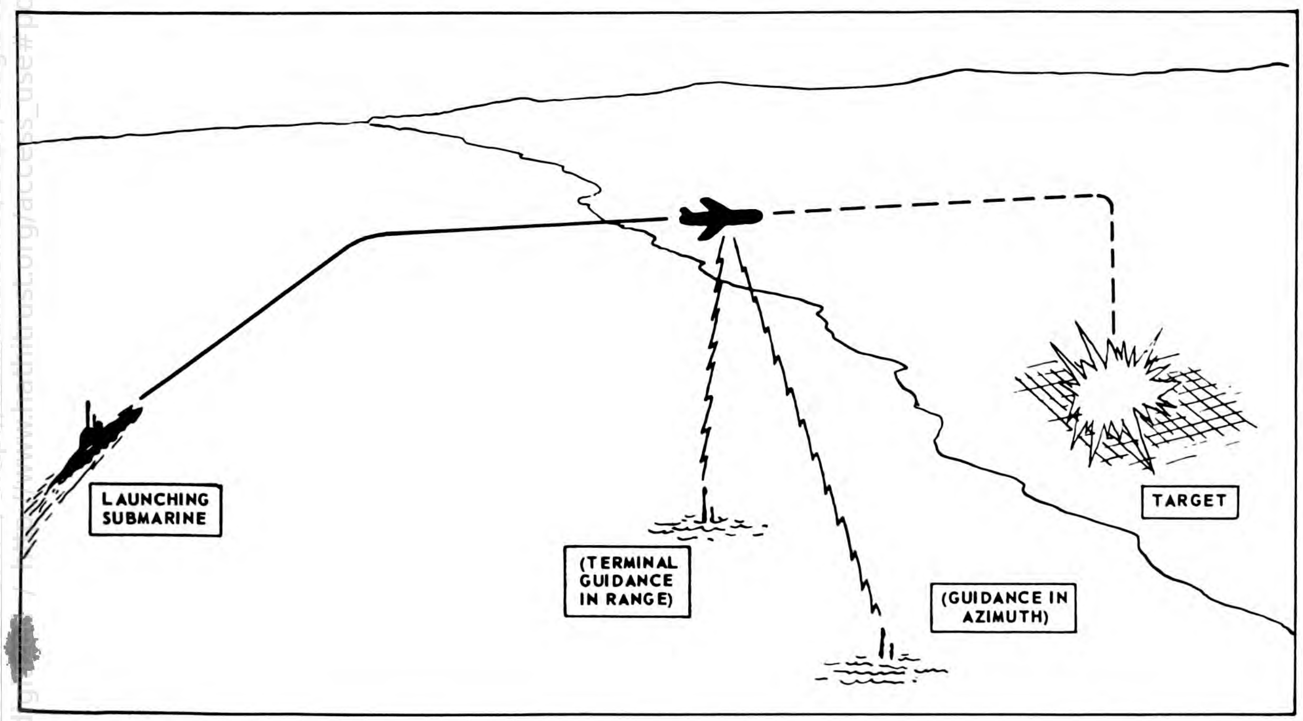

Figure 11D3.—SSM flight.

E. Aircraft Missile Systems

11E1. General

There are two broad classifications of aircraft missile systems: air-to-air and air-to-ground. The Sidewinder and Sparrow families are examples of AAM systems. Bullpup and Corvus are Navy ASM systems. Figures 11E1, 11E2, and 11E3 are pictures of the Sparrow, Sidewinder, and Bullpup missiles on appropriately configured aircraft.

This section will take up the Sparrow family as a typical aircraft missile system. The student will recall that there are three major missiles in the Sparrow family. Sparrow II will not become operational in the U. S. Navy. Sparrow III, while in many respects greatly different from Sparrow I, has the same general characteristics such as length, weight, and configuration.

11E2. The aircraft (Sparrow) missile system

There are four major subsystems that can be considered to make up the Sparrow missile system: These are:

the missile,
the aircraft carrier (or land base),
the aircraft, and
the missile guidance equipment.

The Sparrow I missile is a beam rider. It includes a war head, an influence fuse, a guidance and control section, power supplies, and a rocket motor. Sparrow I was the nation's first air-to-air guided missile, and is much less sophisticated in guidance principles than its more recent sister, the Sparrow III. Sparrow I is an optically sighted beam rider, while Sparrow III is fully radar operated. Both missiles fulfill the design requisite of having a high single-shot probability of kill and a range longer than can be achieved with conventional AA guns. Up to four Sparrow missiles are carried on appropriately configured aircraft. Missile aircraft can also carry mixed loads of Sparrow and Sidewinder missiles.

Additional data concerning specific airborne missiles is contained in chapter 1, and in the confidential supplement to this text.

The AIRCRAFT CARRIER (or land base) is needed to provide operational and logistic

Figure 11E1.—F3H "Demon" with Sparrow missiles.

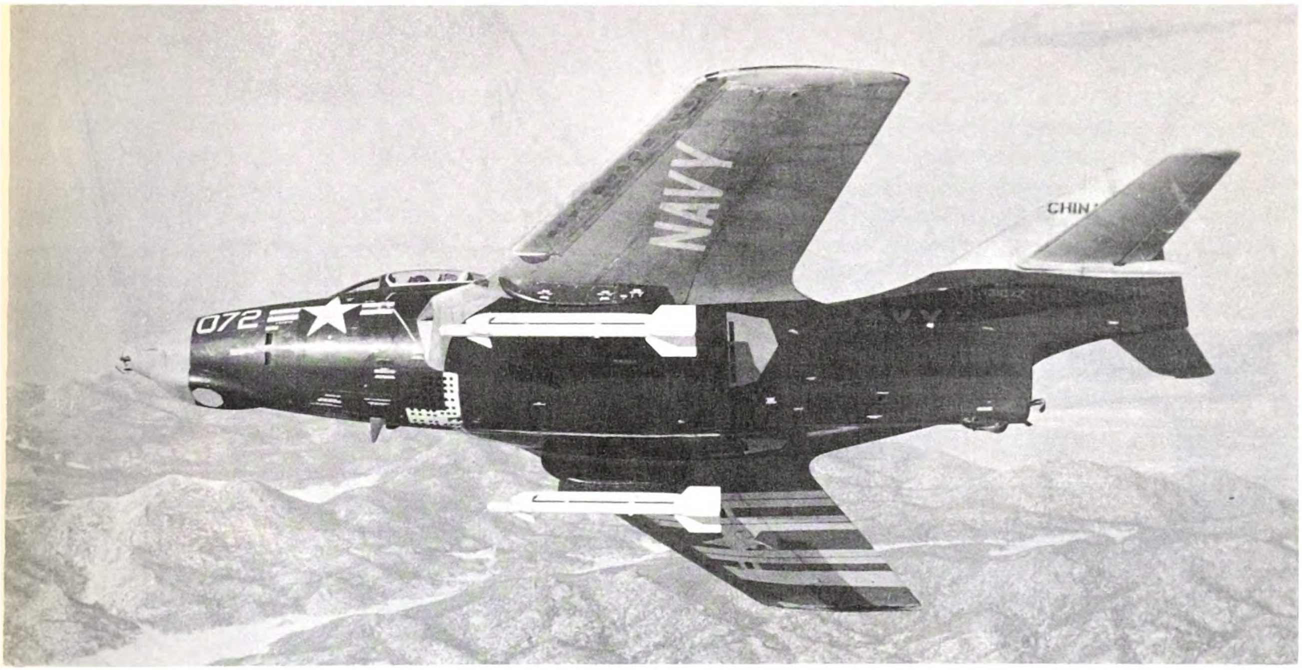

Figure 11E2.—F9F "Cougar" with Sidewinder missiles.

support for the missile and missile aircraft. Test Equipment, training facilities, and provisions for handling and stowage are included on the mobile base. Additionally, as integral parts of the system, are the fighter director facilities which must direct the missile aircraft to the vicinity of the target. Maintenance of the missile is on a "Go-No-Go" basis, as is the practice with many other operational missiles. That is, missiles which do not pass surveillance or pre-flight tests are rejected, and defective sections are returned to centralized maintenance facilities for repair or overhaul. This system speeds up acceptance testing, and eliminates the widespread need for extensive maintenance facilities.

The missile AIRCRAFT is of course the delivery vehicle. Aircraft configured to carry and launch radar-guided missiles must carry extensive electronic equipment for missile guidance. Other equipment to aid in target acquisition, and to furnish "course-to-steer" and "in-range" information, may also be included on the aircraft as part of the missile system.

The last subsystem is that of the MISSILE GUIDANCE EQUIPMENT. The principle function of this equipment is to determine the displacement of the missile from the tracking radar beam, and to send the necessary control information to the missile so that the missile will fly the beam.

11E3. The air-to-air missile problem

To illustrate the AAM missile problem, let us take the classic example of an aircraft carrier providing air cover for a task force at sea. Our missile aircraft will be alerted to the presence of an enemy bomber by the force fighter director organization. The missile aircraft will be vectored to the general vicinity of the enemy, where it will be in a position to acquire the target. A proper pursuit course is then followed until firing range is reached. When within range, the missile is fired and is captured by the guidance radar beam. The missile then follows the guidance beam until within destructive range of the target, where an influence fuse will detonate the war head. The above description is of the basic AAM beam-rider system. The more sophisticated the missile system becomes, the more automatic the various steps become.

Figure 11E3.—FJ "Fury" with Bullpup missiles.

The earliest AAM missiles required visual contact and mental computations, whereas the latest systems perform most of the steps automatically.

Bibliography

Until the confidential supplement to this text is made available, the following material may be consulted for further information on the Navy's guided missile ships and systems.

Guided Missile Systems of the Department of the Navy, dated 3/12/58. Copies should be requested from the Chief, BuOrd (ReS), Navy Department, Washington 25, D. C.
BuOrd Information Bulletins
Navy Department technical manuals on specific missiles or systems.

Part 2

NUCLEAR WEAPONS

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CHAPTER 12

FUNDAMENTALS OF NUCLEAR PHYSICS

A. Introduction

12A1. Scope

This chapter will deal with the aspects of physics that pertain to the structure of the atom, the nature of its component parts, and the predictable behavior of the several atomic components. It will also glance very briefly at the means man has developed, or is now developing, for the liberation of the energy available in the atomic nucleus.

Within the limits allowed by security, subsequent chapters will trace the military uses of nuclear energy.

12A2. Why study the atom?

Readers of this text may not remember, and may find it hard to imagine, what life was like before the wonders and perils of atomic power became a daily theme for cartoonists, headline writers, and microphone orators.

The average citizen is likely to think of the atomic age as dating from the destruction of Hiroshima. Actually the bomb that burst there was not a true beginning; it was simply a world-shaking announcement of an already accomplished fact. Behind the Hiroshima explosion lay a half-century and more of research, speculation, and calculation. Directly behind it, at a distance of almost three years, lay the event that might better be used to mark the dawn of the atomic era.

This earlier event made no headlines, for it was a strictly guarded military secret. It happened in the late autumn of 1942, almost a year to the day after the attack on Pearl Harbor. A group of physicists, chemists, and mathematicians, hand-picked for a special Government project, had for some time been building a mound, shaped somewhat like a huge doorknob, in a shielded area under the unused stadium belonging to the University of Chicago.

The bricks in the mound were carbon. Every second brick had a lump of uranium—or, when economy demanded, uranium oxide—imbedded in it. As the work progressed, detecting instruments were set up and movable cadmium strips and rods were incorporated in the structure. Arrangements were made for observation and control from beyond the safety shields.

On 2 December a number of these scientists—acting under the general direction of the Italian-born nuclear physicist E. Fermi and under the group leadership of W. H. Zinn, H. L. Anderson, and V. C. Wilson—met to test the truth or falsity of the hypothesis that their research (and that of other specialists) had forced upon them. While designated men read the indicating instruments, others removed all but one of the cadmium strips, then pulled slowly on the remaining strip. With mingled feelings, including horror, they saw that their predictions had been correct.

Energy, in measurable and controllable amounts, was being generated in the mound. The source of that energy lay deep at the center of one special kind of uranium atom. The quantities of energy available were fantastically out of proportion to the size of the source. For better or for worse—or for better AND for worse—the atomic age had become a reality.

Since the end of World War II, as every reader of this text is undoubtedly aware, the military and industrial applications of atomic energy have become a major concern of the United States, its potential allies, and its potential enemies. Much military thinking has been revised, and much more is in the process of revision. Regardless of his specialty, no military man can afford to ignore the atom. It is hoped that these chapters will prepare prospective naval officers to make further studies and to follow new developments.

12A3. Objectives

This chapter will take up, first of all, the nature of matter. It will start with a brief summary of the "conventional" ideas that were taught early in the twentieth century. Many of these ideas are still valid; they have been supplemented, rather than superseded, by the results of atomic research. The major emphasis, of course, will be on the atom and its component particles.

The second major division of the chapter will deal with radioactivity. This phenomenon gave scientists some of their most significant clues as to the nature of the atom. Because of their bearing on health and safety, the radioactive by-products of atomic fuel and atomic explosives are likely to be an increasing concern of industrialists, community leaders, and military officers.

The latter part of the chapter will be concerned with nuclear reactions. These reactions are the real source of the power that is popularly called atomic energy.

B. Nature of Matter

12B1. Conventional ideas

About 1900 a chemist, if requested to explain the material world in non-technical language, would have spoken somewhat as follows, stressing certain facts which, as has already been implied, are STILL VALID and are STILL FUNDAMENTAL to an understanding of more recent discoveries.

ELEMENTS. All material is made up of one or more elements. These are substances that cannot be broken down into other and simpler substances by any chemical means. Ninety-two elements are found in nature, some of them in very small amounts.

Iron, mercury, and oxygen—existing at normal temperatures as a solid, a liquid, and a gas respectively—are typical elements. By heating, a solid element can be changed to a liquid and even to a gas. By cooling, a gaseous element can be changed to a liquid and even to a solid.

The smallest portion of any element that shares the general characteristics of that element is called an ATOM, which is Greek for INDIVISIBLE PARTICLE.

MIXTURES. Elements may be mixed without necessarily undergoing any chemical change. For example, if finely powdered iron and sulfur are stirred and shaken together, the result is a mixture. Even if it were possible to grind this mixture to atom-size particles, the iron atoms and the sulfur atoms would remain distinct from each other.

COMPOUNDS. Under certain conditions, however, two or more elements can be brought together in such a way that they unite chemically to form a compound. The resulting substance may differ widely from any of its component elements. For example, drinking water is formed by the chemical union of two gases, hydrogen and oxygen; table salt is compounded from chlorine, a gas, and sodium, a metal.

Whenever a compound is produced, two or more atoms of the combining elements join chemically to form the MOLECULE that is typical of the compound. The molecule is the smallest unit that shares the distinguishing characteristics of a compound.

ATOMIC WEIGHT. Hydrogen is the lightest element. Experiments have demonstrated that the oxygen atom is almost exactly 16 times as heavy as the hydrogen atom. Chemists express this truth by saying that oxygen has an atomic weight of 16. Continued experimentation has determined the atomic weights of the remaining elements.

TABLE. Figure 12B1 is a standard table of the elements. The atomic weight of each element appears below its name. The vertical columns represent family groups. All members—from lightest to heaviest—of a family behave like one another in forming (or in refusing to form) chemical compounds with other families.

To meet current needs, the foregoing discussion of matter must be supplemented (but not replaced) by an analysis of the atom. In 1900, only a few advanced scientists had become convinced that the atom is not INDIVISIBLE after all. By 1920, the complexity of the atom had become common knowledge. The analysis of the several atomic components was still incomplete; but much of the theory of the 1920 period is still recognized as valid, and must be understood before later and more detailed studies can be undertaken.

12B2. Atomic structure, early interpretation

The upper half of figure 12B2 shows the hydrogen and the oxygen atom as they were

PERIODIC ARRANGEMENT OF THE ELEMENTS

Series	Period	ZERO GROUP	GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V	GROUP VI	GROUP VII	GROUP VIII		
0												
1			HYDROGEN H=1.0078 No. 1									
2	1	HELIUM He.=4.002 No. 2	LITHIUM Li.=6.940 No. 3	BERYLLIUM Be.=9.02 No. 4	BORON B.=10.82 No. 5	CARBON C.=12.00 No. 6	NITROGEN N.=14.008 No. 7	OXYGEN O.=16.000 No. 8	FLUORINE F.=19.00 No. 9			
3	2	NEON Ne.=20.183 No. 10	SODIUM Na.=22.997 No. 11	MAGNESIUM Mg.=24.32 No. 12	ALUMINUM Al=26.97 No. 13	SILICON Si.=28.06 No. 14	PHOSPHORUS P=31.02 No. 15	SULFUR S=32.06 No. 16	CHLORINE Cl.=35.457 No. 17			
4	3	ARGON A.=39.944 No. 18	POTASSIUM K.=39.10 No 19	CALCIUM Ca.=40.08 No. 20	SCANDIUM Sc.=45.10 No. 21	TITANIUM Ti.=47.90 No. 22	VANADIUM V.=50.95 No. 23	CHROMIUM Cr.=52.01 No. 24	MANGANESE Mn.=54.93 No. 25	IRON Fe.=55.84 No. 26	COBALT Co.=58.94 No. 27	NICKEL Ni.=58.69 No. 28
5			COPPER Cu.=63.57 No 29	ZINC Zn.=65.38 No. 30	GALLIUM Ga.=69.72 No. 31	GERMANIUM Ge.=72 60 No. 32	ARSENIC As.=74.93 No. 33	SELENIUM Se.=79.2 No 34	BROMINE Br.=79.916 No. 35			
6	4	KRYPTON Kr.=82.9 No. 36	RUBIDIUM Rb.=85.44 No. 37	STRONTIUM Sr.=87.63 No. 38	YTTRIUM Y.=88.92 No. 39	ZIRCONIUM Zr.=91.22 No. 40	COLUMBIUM Cb.=93.3 No. 41	MOLYBDENUM Mo.=96.0 No. 42	MASURIUM Ma.=? No. 43	RUTHENIUM Ru.=101.7 No. 44	RHODIUM Rh.=102.91 No. 45	PALLADIUM Pd.=106.7 No. 46
7			SILVER Ag.=107.880 No. 47	CADMIUM Cd.=112.41 No. 48	INDIUM In.=114.8 No. 49	TIN Sn.=118.70 No. 50	ANTIMONY Sb.=121.76 No. 51	TELLURIUM Te.=127.5 No. 52	IODINE I.=126.932 No. 53			
8	5	XENON Xe.=130.2 No. 54	CAESIUM Cs.=132.81 No. 55	BARIUM Ba.=137.36 No. 56	LANTHANUM La.=138.90 No. 57	CERIUM Ce.=140.13 No. 58						
9												
10	6					HAFNIUM Hf.=178.6 No. 72	TANTALUM Ta.=181.4 No. 73	TUNGSTEN W.=184.0 No. 74	RHENIUM Re.=186.31 No. 75	OSMIUM Os.=190.8 No. 76	IRIDIUM Ir.=193.1 No. 77	PLATINUM Pt.=195.23 No. 78
11			GOLD Au.=197.2 No. 79	MERCURY Hg.=200.61 No. 80	THALLIUM Tl.=204.39 No. 81	LEAD Pb.=207.22 No. 82	BISMUTH Bi.=209.00 No. 83	POLONIUM Po.=209.99 No. 84	ALABAMINE Am.=? No. 85			
12	7	RADON Rn.=222 No. 86	VIRGINIUM Va.=? No. 87	RADIUM Ra.=225.97 No. 88	ACTINIUM Ac.=227.02 No. 89	THORIUM Th.=232.12 No. 90	PROTO-ACTINIUM Pa.=231.03 No. 91	URANIUM U.=238.14 No. 92	No. 93			

ELEMENTS NOT CLASSIFIED IN THE TABLE ABOVE

PRASEODYMIUM Pr.=140.92 No. 59	NEODYMIUM Nd.=144.27 No. 60	ILLINIUM Il.=146.(?) No. 61	SAMARIUM Sm.=150.43 No. 62	EUROPIUM Eu.=152.0 No. 63	GADOLINIUM Gd.=157.3 No. 64	TERBIUM Tb.=195.2 No. 65
DYSPROSIUM Dy.=162.46 No. 66	HOLMIUM Ho.=163.5 No. 67	ERBIUM Er.=167.64 No. 68	THULIUM Tm.=169.4 No. 69	YTTERBIUM Yb.=173.5 No. 70	LUTECIUM Lu.=175.0 No. 71	

Figure 12B1.—Standard table of the elements.

pictured in the average science classroom during the 1920's.

NUCLEUS AND ELECTRONS. As shown in these sketches, the atom is not solid at all; in fact, it consists largely of empty space. At the center of each atom is a small amount of substance, extremely heavy for its size, called the NUCLEUS.

In the hydrogen atom a single very light particle, called an ELECTRON, travels in an orbit around the nucleus and spins meanwhile on an axis of its own. Very roughly speaking, this electron is to the nucleus as the earth is to the sun. (It is often called an ORBITAL or PLANETARY electron, to distinguish it from another kind that was later identified.)

The electron bears a charge of static electricity, of the type that physicists have arbitrarily called negative. A single positive charge on the hydrogen nucleus balances the negative charge on this electron. Thus, in its normal or "unexcited" state, the hydrogen atom as a whole is electrically neutral.

Helium, the element next heavier than hydrogen, has two electrons that travel in a single orbit. Two positive charges on the helium nucleus counterbalance the negative effect of the two electrons.

Lithium, the next heavier element, has three electrons. Only two of these travel in the comparatively small area near the nucleus; the third has a much larger orbit. The lithium nucleus has three positive charges.

If time and space permitted, the atoms of all the elements could be examined one by one. For present purposes, however, the oxygen atom (fig. 12B2, upper right) will be an adequate example.

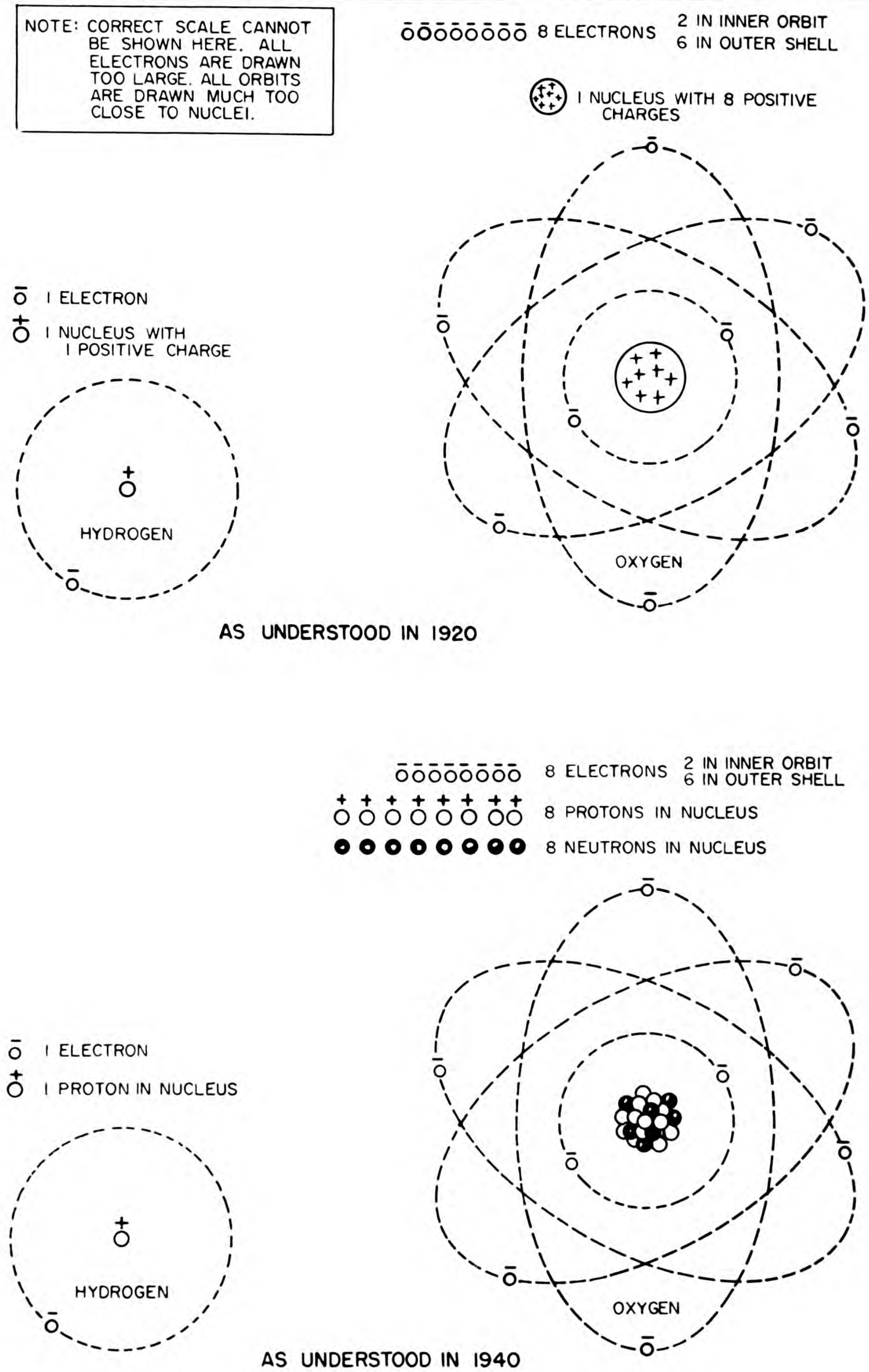

Figure 12B2.—Changing interpretation of the atom.

The oxygen atom has eight electrons, and therefore eight positive charges on its nucleus. The first two electrons are in the inner orbit, as is normal in any atom above hydrogen. Three outer orbits, all equidistant from the nucleus but each lying in a separate plane, contain the other three pairs of electrons, as shown in the drawing. We can think of the six outer electrons, all revolving and spinning, as tracing a hollow shell like an ultra-light tennis ball. Scientists customarily speak of electrons as being located IN SHELLS.

Under normal conditions, there is a limit to the number of electrons a given shell can contain. After this limit has been reached, the next heavier element in the table (fig. 12B1) starts a new shell with a much longer diameter. Uranium, the heaviest NATURAL element, has 92 electrons arranged in seven concentric shells.

CHEMICAL IMPLICATIONS. The outermost shell of any atom concerns the chemist in particular. Two atoms with completely filled outer shells won't unite to form a molecule; this is why some substances cannot be combined chemically. An atom with vacant spaces in its outer shell can fill those spaces by sharing certain electrons of other atoms; in this way molecules are built up.

In the oxygen atom six electrons are located in an outer shell that has room for eight. For this reason the oxygen atom can be made to share the electrons of two hydrogen atoms, thus creating a water molecule as shown in figure 12B3. (For the sake of simplicity, the figure shows all the electrons as though they were in one plane; this is not really correct.) As long as they remain chemically united, the combining atoms have, in effect, a single outer shell that gives the molecule its distinctive character.

One fact about the NUCLEUS is important to the chemist. The number of positive charges is a key to the chemical identity of any element. Hydrogen is hydrogen because its nucleus has one positive charge; uranium is uranium because its nucleus has 92 positive charges. (This fact will be more understandable after subsequent studies.)

ELECTRICAL IMPLICATIONS. Some atoms can, under one condition or another, be made to give up an outer electron rather easily.

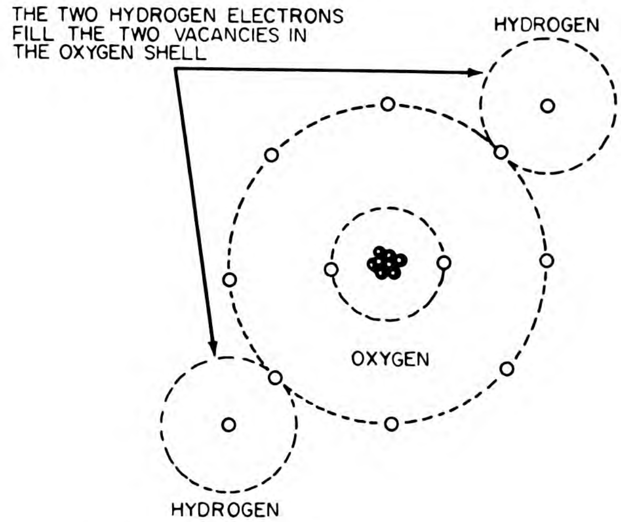

Figure 12B3.–A molecule is formed by a union of outer shells.

This FREE or STRAY electron takes its negative charge with it as it moves away, seeking some atom with a vacant space in its outer shell. Electric current consists of free electrons in motion.

A molecule or atom that has temporarily lost an electron (and consequently bears an unbalanced positive charge) is called a POSITIVE ION. A molecule or atom that has temporarily gained a surplus electron is a NEGATIVE ION.

Ionization does not alter the nucleus, and therefore does not change one element to another. As soon as conditions permit, an ionized particle reverts to its balanced or electrically neutral state.

INFORMATION STILL LACKING. Like a 1900 lecture on matter, the foregoing 1920 interpretation of the atom is correct in the statements it makes. Its fault lies in a lack of complete understanding of the atomic nucleus. Research scientists acquired this understanding bit by bit, over many years. Even now, some details need further clarification. Between the two world wars, however, the results of many nuclear studies began to fit together like a jigsaw puzzle. By 1940 the men of science, but not the general public, had become aware of the far-reaching implications of nuclear physics.

12B3. Atomic structure, present interpretation

The lower part of figure 12B2 shows the hydrogen and oxygen atoms as they are now understood. The planetary electrons look much the same as in the upper half of the drawing. The hydrogen nucleus has gained nothing except a new name; now, if one desires, he may refer to this simple nucleus as a PROTON. The oxygen nucleus, however, has lost its early simplicity. It is now a tight cluster of small pellets. There are sixteen pellets, some of which are hidden by perspective.

PROTONS. Eight of the particles in the oxygen nucleus are positively charged. These are the protons. They are equal in number to the planetary electrons, but they are vastly heavier. It is really an atom's complement of protons that determines what element it represents and how it reacts in chemical experiments. In any normal atom, the protons and the planetary electrons are equal in number, just as they are in oxygen.

NEUTRONS. In addition to the eight protons, the oxygen nucleus contains eight uncharged particles, each equivalent (for all practical purposes) to a proton in size and weight. These heavy but uncharged nuclear particles are the neutrons; they are tremendously important in nuclear physics.

With the single exception of hydrogen in its simplest form, all atomic nuclei contain neutrons as well as protons. The lighter elements tend to have approximately equal quotas of the two kinds of particles; the heavier elements have more neutrons than protons.

The covering word NUCLEONS is often used when one wishes to refer to BOTH neutrons and protons; similarly, nuclear physics is sometimes called nucleonics.

SOME FACTS ABOUT WEIGHT. Because electrons are extremely light, their total effect on the weight of any atom is negligible. But neutrons and protons are both heavy. The atomic weight of an element, as measured in the chemical laboratory, reflects the total number of nucleons in the atom, not merely the number of protons. This explains the fact (puzzling to early chemists) that oxygen, with only eight times the number of positive charges, is almost sixteen times as heavy as hydrogen.

The subsequent article on isotopes will account for another puzzling phenomenon; namely, the fractional components of the atomic weights shown on conventional tables like figure 12B1.

LOOKING AHEAD. Electrons, protons, and neutrons are not the only particles that occur in atoms. Nevertheless two important topics—isotopes and the nuclear physicist's symbols—can and will be introduced before the other atomic particles are listed.

12B4. Isotopes

As already mentioned, the atomic weights shown in figure 12B1 were determined by chemical processes. Therefore the present tendency is to call them CHEMICAL ATOMIC WEIGHTS. The chemical atomic weight usually differs by a small fraction from some whole number; in a few instances the fraction is large. The presence of the fraction defied explanation until the neutron was discovered and studied.

Nuclear studies revealed that atoms which have the same complement of protons (and therefore are chemically identical) may vary in their complement of neutrons. The variant forms of any given element are called its ISOTOPES.

Hydrogen has three isotopes. The most abundant hydrogen isotope has one proton and no neutron, as shown in figure 12B2. One isotope of hydrogen—called deuterium or, more popularly, heavy hydrogen—has one proton and one neutron. The third isotope, tritium, has one proton and two neutrons. See figure 12B4.

When isotopes occur in nature, the ratio of one isotope to the other(s) tends to remain constant in all samples of a given element. Because a laboratory sample contains all the natural isotopes, and because all the neutrons in the sample enter into the measurement of the chemical atomic weight, this weight has a fractional component.

Isotopes will be mentioned frequently in later parts of this chapter and volume.

12B5. Nuclear symbols

Before the discovery of the neutron, scientists identified any atom by a one-letter or two-letter symbol representing its chemical name—H for hydrogen, Cl for chlorine, Na for sodium (whose latinized technical name is natrium), and so on. The nuclear physicist accepts these time-honored letter symbols; when speaking in

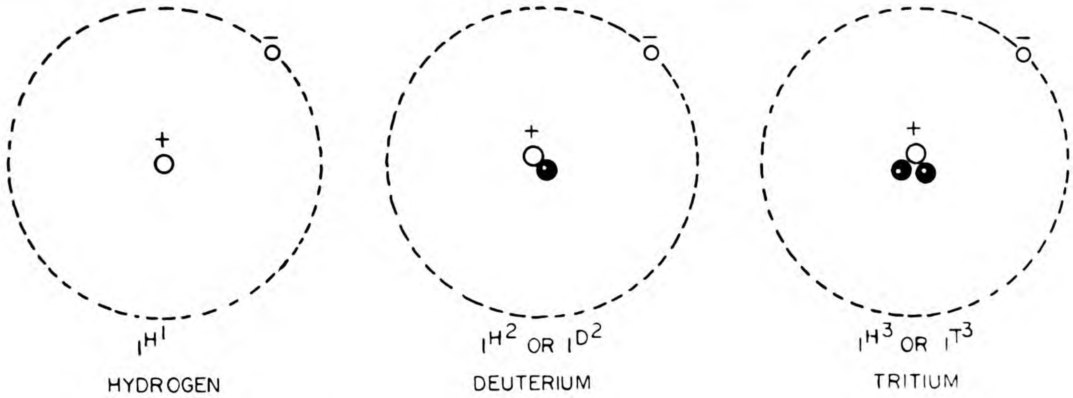

Figure 12B4.–The three hydrogen isotopes.

general terms he refers to any of them as SYMBOL X.

To make precise reference to a given atom, the nuclear physicist (1) precedes symbol X with a numerical subscript called SYMBOL Z and (2) follows symbol X with a number (often, but not always, written as a superscript) called SYMBOL A. His identification of an atom, then, takes the form $_zX^A$ or $_zXA$ or sometimes, when Z is clearly understood from the context, simply X^A or XA.

SYMBOL Z. The subscript Z is called the ATOMIC NUMBER; it tells how many protons the nucleus contains (and simultaneously, of course, how many planetary electrons the atom has in its normal state). For hydrogen Z is 1; for oxygen it is 8; for uranium it is 92.

SYMBOL A. The final identifying symbol is an ATOMIC MASS NUMBER representing the nucleons; that is, the sum of the protons and the neutrons. For the most common hydrogen isotope A is 1; for deuterium it is 2; for tritium it is 3. For the most abundant isotope of uranium, A is 238.

To find the number of neutrons in any fully identified atom, subtract Z from A.

Note: The reader may sometimes see the term ATOMIC WEIGHT used for symbol A. It is preferable, however, to restrict this older term to its original sense of CHEMICAL ATOMIC WEIGHT and to use ATOMIC MASS NUMBER or simply MASS NUMBER for symbol A.

The accompanying table shows the interpretation of a few nuclear symbols.

Interpreting Nuclear Symbols

Substance Symbol	Protons (Z)	Total Nucleons (A)	Neutrons (A-Z)	Electrons (=Z)
Common hydrogen $_1H^1$	1	1	0	1
Deuterium $_1H^2$ or $_1D^2$	1	2	1	1
Tritium $_1H^3$ or $_1T^3$	1	3	2	1
Oxygen $_8O^{16}$	8	16	8	8
Uranium $_{92}U^{238}$	92	238	146	92

12B6. Other nuclear particles

Observations of nuclear radiation (the phenomenon taken up in section C of this chapter) and other nuclear reactions have shown that an atomic nucleus does not always consist solely of protons and neutrons.

In the first place, the neutron itself is not indivisible. If set free from the nucleus, it breaks down or DECAYS sooner or later into a proton, an electron, and an uncharged particle called a NEUTRINO. (The neutrino need not concern the student further in this course.)

The electron liberated by neutron decay is called a BETA PARTICLE to distinguish it from a planetary electron. The equal and opposite charges on its component proton and beta

particle give the neutron as a whole its electrically neutral character.

Under some conditions, an excited nucleus emits positively charged beta particles. These are called POSITRONS or POSITIVE ELECTRONS.

A large particle consisting of two protons and two neutrons is emitted in some reactions. This unit, which is essentially a free helium nucleus, is called an ALPHA PARTICLE. If and when an alpha particle acquires two electrons, it becomes a helium atom.

A DEUTERON is an emitted particle consisting of a proton and a neutron. It is, therefore, the same as the heavy hydrogen nucleus.

A TRITON consists of a proton and two neutrons. It is the same as the nucleus of tritium, the third hydrogen isotope.

Another term defined for purposes of orientation (but which should not further concern the student at this time) is the MESON, or as it is cometimes called, the mesotron. The meson is a short-lived particle that may sometimes be found with either a positive, negative, or zero charge. The mass of the meson is also variable, sometimes being 200 or 300 times the mass of an electron.

Additionally, there is the GAMMA RAY, which while being a form of electromagnetic radiation, sometimes behaves as a nuclear particle. The gamma ray originates from the atomic nucleus, carries no charge, and is highly penetrating. The X-ray can be considered very similar to the gamma ray except that the wavelength of the former is longer. Gamma radiation is the most significant of the radiological hazards of nuclear explosions.

Later sections and chapters of this text will assume that the reader is familiar with the names and definitions of these several nuclear components. Because exploration of the nucleus is still going on, a time may come when the present definitions will have to be revised and new definitions added.

12B7. Expanded table

The discovery of a great multiplicity of isotopes (some natural and some man-made) soon overtaxed the capacity of the conventional table shown in figure 12B1. The student of atomic phenomena now refers to a much more comprehensive table in which all known NUCLIDES (separate species of atomic nuclei) are arranged in an orderly number by ascending values of mass number and neutron complement.

Figure 12B5 shows accurately (but necessarily to very small scale) the shape of this table as a whole. Small excerpts from the table, enlarged to show the notations concerning individual nuclides, appear in figures 12B5, 12B6, and 12B7. Sections C and D of this chapter will refer to these excerpts.

In this comprehensive table, each block represents a nuclide. The value of Z (that is, the number of protons and therefore the chemical nature of the substance) is determined by the vertical distance from the base line to the given block. This arrangement places isotopes in horizontal rows.

The value of A-Z (that is, the number of neutrons) is determined by the horizontal distance of the block to the right of the extreme left line. The atomic mass number (symbol A) is printed after the chemical letter symbol at the top of the block.

12B8. Chemical versus nuclear reactions

This topic will receive only brief notice at this time. The underlying theory will receive some attention in section D of this chapter. The practical importance will become evident in later chapters.

CHEMICAL. When two atoms unite chemically to form a molecule—or even when several types of molecules break apart and their atoms recombine in new molecules—the planetary electrons in the outer shells are the only atomic particles involved in the transformation. The several nuclei remain as they were before.

Chemical reactions are frequently marked by the release of usable amounts of kinetic energy, as when gasoline burns or TNT detonates. The quantity of energy thus produced is small, in proportion to the number of molecules involved in the reaction.

NUCLEAR. When an atomic nucleus gains or loses one or more PROTONS, the parent element is changed or TRANSMUTED to another element. (This is the feat the medieval alchemists tried in vain to accomplish.) When a nucleus gains or loses a neutron, it becomes a different isotope.

These nuclear reactions are always accompanied by a release of kinetic energy. The ratio of energy release to the number of atoms

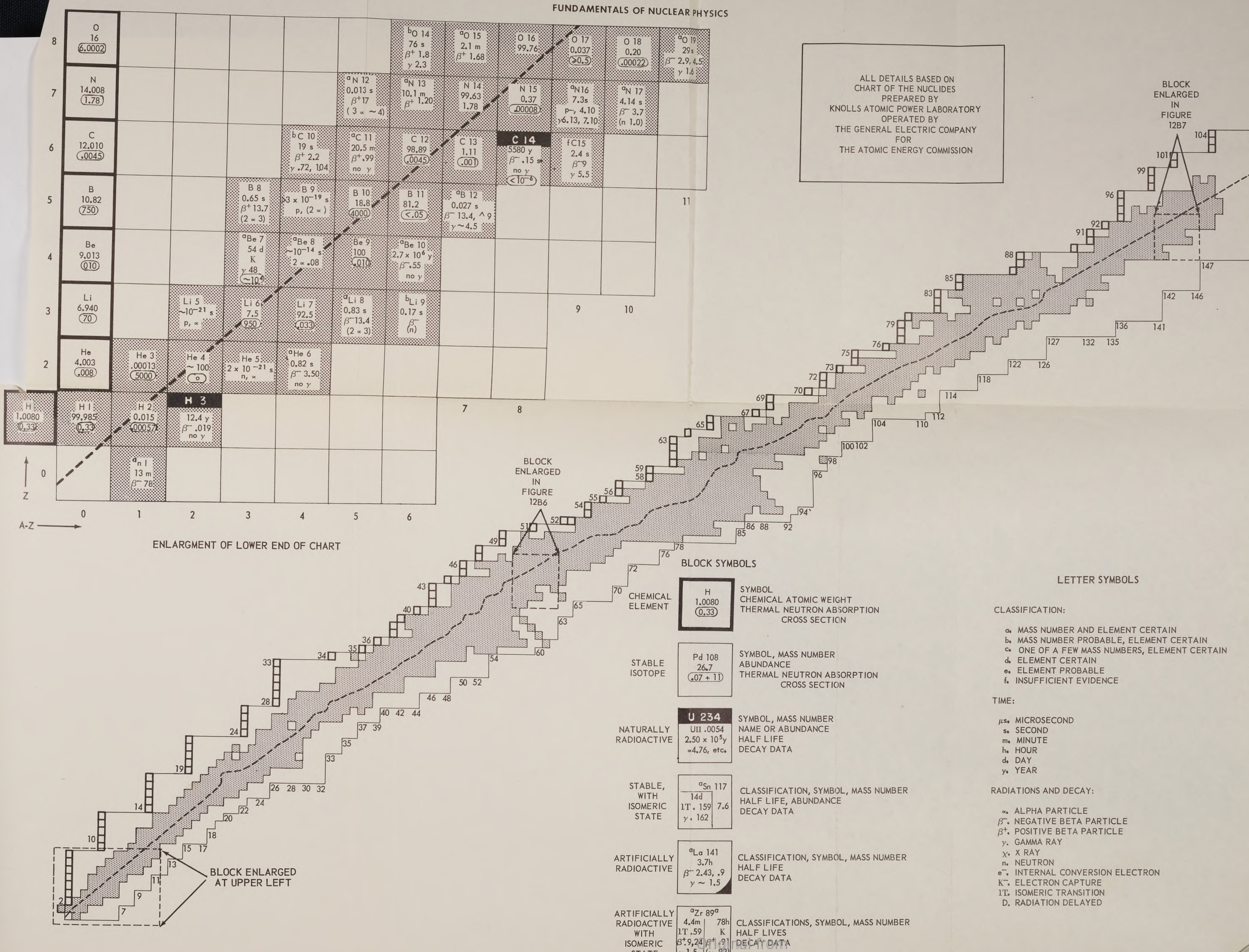

Figure 12B5.—The nuclear physicist's table of the elements.

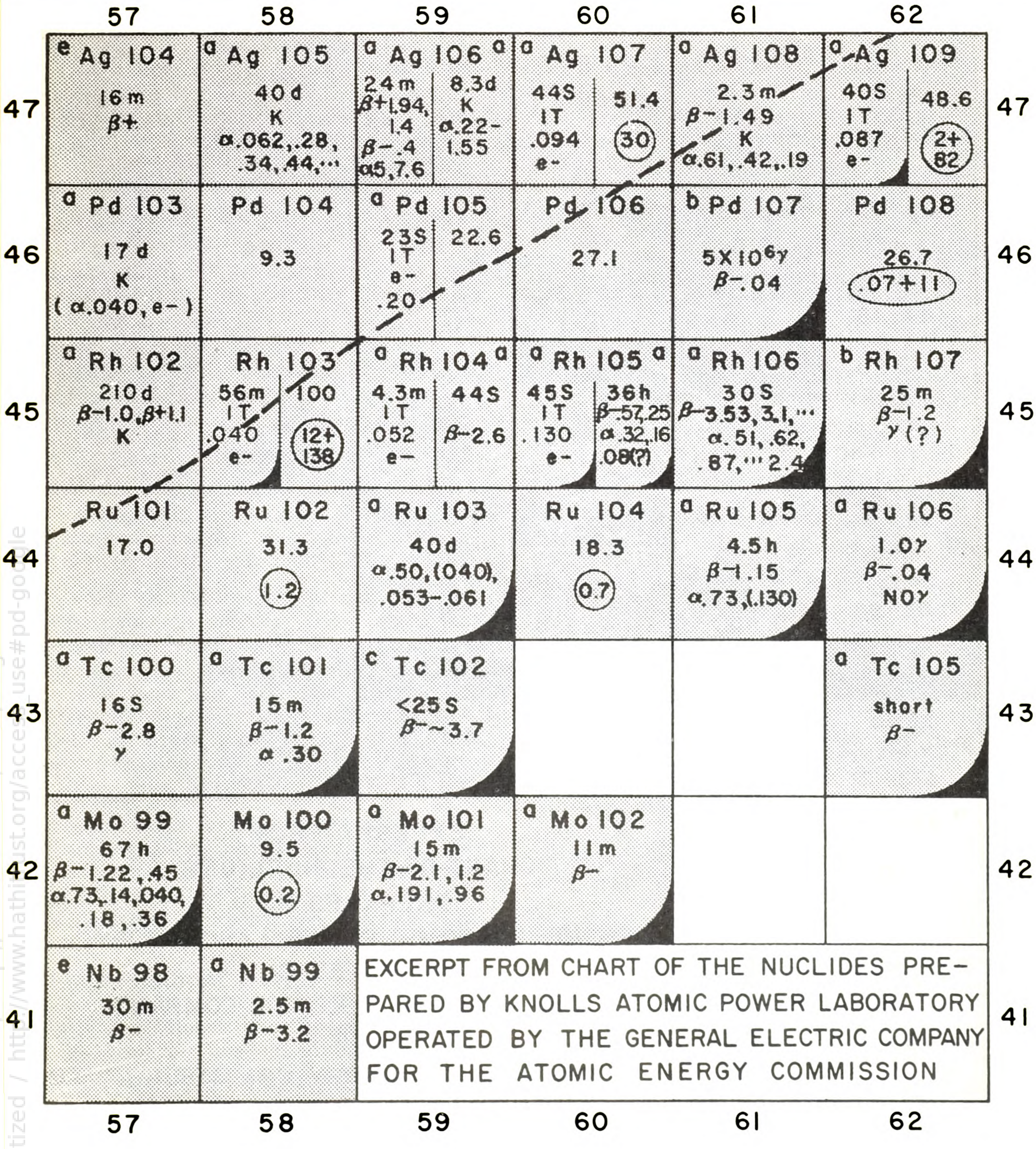

Figure 12B6.—Excerpt from the medium-weight area of the table.

involved is almost incomparably greater than in a chemical reaction. Hiroshima demonstrated the military importance of the atom as a source of energy. Mankind has just begun to utilize the non-military possibilities.

	141	142	143	144	145	146	
94	b Pu 235 26 m L,K α5.85	a Pu 236 2.7γ α5.75 γ.04,e−	b Pu 237 ~40d K NOγ	a Pu 238 90γ α5.49,5.45 γ0.45,0.48 400	Pu 239 24,300γ α5.15,5.14,5.10 γ.052,e−	a Pu 240 6600γ α5.16,5.12	94
93	a Np 234 4.4d L,K γ1.42,.80, .44,.18	a Np 235 410d L,K α5.06	a Np 236 22h L,K β−.51,.36 γ.15,e−	a Np 237 2.2×10^6γ α4.77 γ~.05,e− 150	a Np 238 2.10d β−.26,1.27 γ1.0,.10,.05	a Np 239 3.23d β−.31−.71 γ.04−.23, .280	93
92	a U 233 1.62×10^5γ α4.80 γ0.39,0.80, .36,e−	U 234 U II .0054 2.50×10^5γ α4.76,γ.05−.12 e− 80	U 235 AcU 0.72 7.1×10^8γ α4.40,4.58, 4.20 γ.09−3.6 101	c U 236 2.39×10^7γ α4.50 γ.05,e−	a U 237 6.7d β−~.23,e− γ.20,.06,.26	U 238 U I 99.28 4.51×10^9γ α4.20 γ.05 2.80	92
91	a Pa 232 1.32d β−.33 γ.05−.96	a Pa 233 27.4d β−.23,.53,... γ.31,.03−.42 40	Pa 234 UX2 UZ 1.14m 6.7h β−2.3 β−.45, γ.8 1.2 IT.39 2γ8	b Pa 235 .24m β−1.4 NOγ			91
90	Th 231 Uy 25.6h β−.09,.30,.22 γ.022−.21	Th 232 Th 100 1.39×10^{10}γ α4.03,γ.05 7.0	Th 233 23.3m β−1.23 1400	Th 234 UX 24.10d β−.20,.11 γ.093 1.7	a Th 235 <5m β−		90
89	d Ac 230 <1m β−2.2		EXCERPT FROM CHART OF THE NUCLIDES PREPARED BY KNOLLS ATOMIC POWER LABORATORY OPERATED BY THE GENERAL ELECTRIC COMPANY FOR THE ATOMIC ENERGY COMMISSION				89
88	a Ra 229 <5 m β−	a Ra 230 1 h β−1.2					88
	141	142	143	144	145	146	

Figure 12B7.—Excerpt from the heavy-element area of the table.

C. Radioactivity

12C1. Preliminary

Among the several types of research that led to our present understanding of the atom, few were more significant than the patient, physically hazardous pioneer studies of radioactivity.

By radioactivity we mean the spontaneous emission of particles and photons by certain unstable atomic nuclei.

NATURAL RADIOACTIVITY. Of the 300-odd nuclides found in nature, about 40 are naturally radioactive. With very few exceptions, these naturally radioactive substances are isotopes of the heavy elements at the upper right end of the table of the nuclides. Figure 12B7 is an excerpt from the area where natural radioactivity is comparatively common. It is not surprising that the complex nuclei of the heaviest elements should be unstable; that is, should tend to disintegrate or DECAY.

The early studies of natural radioactivity were conducted on radium, from which the phenomenon receives its name. Radium occurs, in extremely small amounts, in uranium deposits. We know now WHY radium is found associated with uranium; it is formed at one step of a long process by which the unstable isotopes of uranium disintegrate until a stable end product, lead, is reached.

There are three families of naturally radioactive elements—the uranium, thorium, and actinium groups. Each family has a separate isotope of lead as its final product. Natural lead is a mixture of these three isotopes, plus a fourth one.

INDUCED RADIOACTIVITY. Very few of the elements lighter than polonium (Z = 84) have naturally radioactive isotopes. By nuclear reactions, however, man has produced a large number of unstable isotopes not found in nature. The great bulk of these lie in the medium-weight area of the table of the nuclides. Figure 12B6 is a representative excerpt showing artifically radioactive nuclides.

Artifically produced radioactive isotopes have become very useful to medicine and industry. It is probable that still wider uses will be found for some of them.

12C2. Radioactive series decay

As has been mentioned, the three families of naturally radioactive elements disintegrate or decay in a series of steps, until a stable end product is formed. At any step, either an alpha or a beta particle is emitted from each reacting nucleus.

Artifically produced radioactive substances decay in a similar (but frequently much shorter) series of steps until some stable end product is formed. The next paragraphs will describe the types of radiation.

ALPHA RADIATION. As previously noted, alpha particles are essentially helium nuclei. When emitted, these particles travel fast (2,000 to 20,000 miles per second). Because they are large, as compared with other emitted particles, and because they contain protons that are capable of attracting stray electrons, alpha particles are unlikely to penetrate far into barrier substances.

Even if the barrier substance normally contains very few stray electrons, the alpha particles tend to PRODUCE some by colliding with atoms and knocking off planetary electrons. By capturing two free electrons, the alpha particle becomes stabilized as a helium atom. Meanwhile, of course, the formerly normal atoms that have lost electrons remain ionized until they can replace the loss.

BETA RADIATION. The emitted beta particle is a fast-moving free electron. It is more penetrating than the much larger alpha particle. When finally captured as a surplus free electron, the beta particle makes a negative ion of the atom (or molecule) it has joined.

GAMMA RADIATION. The loss of an alpha or a beta particle leaves a radioactive nucleus with an excess quantity (quantum) of energy, which it emits almost immediately as a gamma ray. This extremely high-frequency radiation travels at the speed of light. Like X rays, which they closely resemble, gamma rays are invisible, are capable of darkening photographic plates, and have great penetrating power.

When a gamma ray passes through a normal atom, it is likely to cause a planetary electron to be expelled. This, of course, converts the atom to a position ion. The ray-produced ion and the electron it has lost are called an ION

PAIR. This term will recur in article 12C5, on RADIATION UNITS.

Not all gamma rays cause ionization immediately. In the following reactions, studied under laboratory conditions, the original gamma rays merely start processes that are capable, later, of producing ions. (1) High-velocity gamma rays have been used to bombard certain atoms and thus produce nuclear fission, a topic discussed in the final section of this chapter. (2) Sometimes a gamma ray, in passing close to an atomic nucleus, undergoes conversion to two free electrons—one negatively and one positively charged. (This is an instance of the conversion of energy to mass. See section D of this chapter.) The positive electron (positron) soon collides with a normal electron, with the result that their two masses are converted to energy in the form of two opposite-direction gamma rays.

Another possibility is that a gamma ray may not cause any emission, but may simply give some planetary electron an abnormal amount of energy. As a result, the atom containing this electron becomes "excited" and may emit short-lived flashes of visible light.

The gamma ray, then, is more versatile and potentially more dangerous than the alpha or the beta particle.

PRACTICAL SIGNIFICANCE. Though the topic will be taken up again in greater detail, it is well to note at once that nuclear radiation has great practical significance. Any ionizing process has an effect on the various types of complex molecules in the human (or other animal) body. Depending on a variety of circumstances, the effect can be slight, fairly serious, extremely serious, or fatal.

Before the beginning of the atomic age, radiation hazards and precautions were the concern of medical officers and hospital corpsmen trained in X-ray techniques. Now that nuclear power and nuclear weapons are increasingly common, radiation has become the concern of all officers and men. The remainder of this section will discuss, very briefly, some of the topics that any junior officer should understand in preparation for later and more intensive studies of radiation problems.

12C3. Half life

WHAT IT IS. A student of radioactivity must understand clearly what is meant by HALF LIFE. This term is always included in the complete description of a radioactive nuclide.

The half life is the time required for half the atoms in any given mass of the substance to enter into the decay process. The half life is a CONSTANT for the given substance, regardless of the size of the sample.

Assume that the block shown at the extreme left in figure 12C1 is composed entirely of the radioactive protoactinium isotope known as Pa^{231}. The half life of this particular isotope is 34,000 years. At the end of 34,000 years, therefore, half of the original protoactinium atoms will have undergone transmutation to other elements. The rest will still be protoactinium. If they were separated from the transmuted atoms, the protoactinium atoms would now constitute the second block in figure 12C1.

The second block will not decay completely in the second 34,000-year period. Unquestionably, it has only half as many atoms as the original block; but by that very fact it offers only half the original opportunity for atomic reactions to take place. As before, half of the atoms (a quarter of the original protoactinium atoms) will remain unchanged at the end of the half life.

During the third half life, the number of protoactinium atoms will again be cut in half—and so on. In general terms, then, x pounds of any radioactive isotope will decay in accordance with the following series:

$$\frac{x}{2}+\frac{x}{4}+\frac{x}{8}+\frac{x}{16}+\frac{x}{32}+\frac{x}{64}+\frac{x}{128}+\frac{x}{256}\cdots+\frac{x}{n}$$

No matter how far this series is extended, its final term, x/n will represent only half of the protoactinium atoms that were intact at the beginning of the given half life. If x/n atoms have been lost this time through decay, an equal number still remain to start the next half life.

In other words, the sum of this series APPROACHES x, the original number of atoms but (in theory at least) never quite reaches it. There is always a fraction, equal to x/n, representing the atoms that are still intact.

PRACTICAL APPLICATIONS. Half life has important bearings on safety. It is obvious first of all, that any isotope with a long half life is potentially dangerous if it is produced in large amounts. When such an isotope is

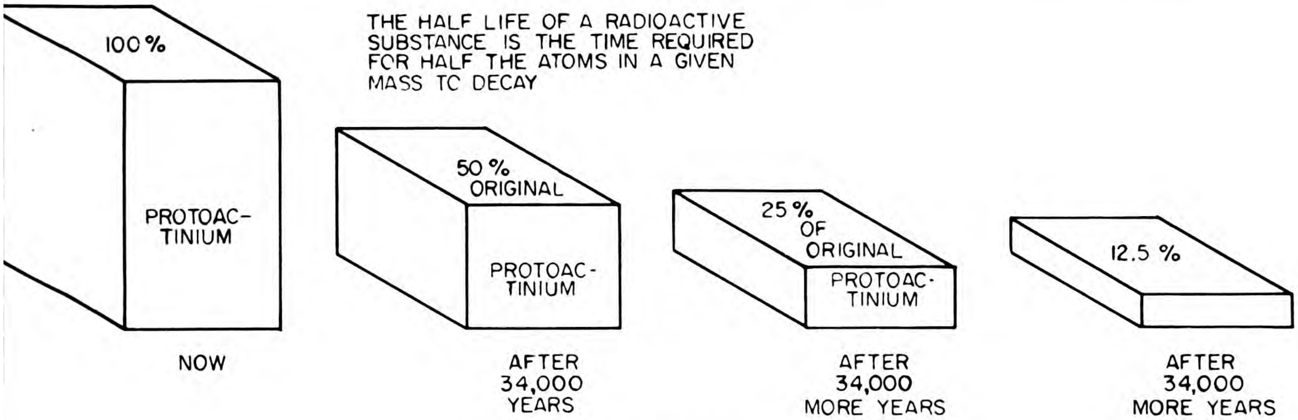

Figure 12C1.—The principle of half life.

nce formed—whether by nature or in an atomic ower plant or during a nuclear explosion—it 'ill contaminate its surroundings for a long ime to come.

For some of the artificially produced radio-ctive isotopes, the half life is measured in ours, minutes, or even seconds. These iso-opes are extremely active; that is why they ecay so fast. They are, therefore, highly angerous for a short time after they are ormed, but the danger diminishes rapidly fter the first few half lives have been com-leted. After a few days (or, in some instances veeks) too few of these radioactive atoms are eft to do much harm.

Another, and very different, application of he half-life principle is in determining the pproximate age of the earth. This has been lone by measuring the proportion of stable ead in uranium deposits and computing the umber of centuries of uranium decay required o form this lead. The earth's age, as deter-nined by this method, is 2.5 billion years. The figure agrees rather closely with those rrived at by other recent calculations.

12C4. Half thickness

As has already been mentioned, radio-active substances emit particles and rays that produce ionizing reactions in previously nor-mal atoms or molecules. Under competent control and with proper safeguards, radiation can be harmless, as when a hospital corpsman takes a chest X ray. It can even be a power for good, as when a surgeon trained in radiology destroys cancerous cells without damaging much of the patient's normal tissue Out of control and without safeguards, radiation can be one of the great hazards of our time.

Article 12C2 explained that alpha particles have low penetrative power. Ordinary clothing, or even unbroken skin, will prevent them from entering the body from the outside. The only way one can suffer much ionization damage from alpha particles is by eating, breathing, or otherwise taking into the system, some radio-active isotopes that will become lodged in the body and remain there through a series of half lives.

Beta particles traveling in air are effective within an approximate 10-foot range of their source. Denser substances, like wood or even water, limit their effective range to about a thousandth of its value in air. Moderate cloth-ing gives substantial (though not complete) pro-tection against beta radiation.

It is, however, the gamma rays produced by all radioactive decay, and the free neutrons that characterize man-made nuclear reactions, that are the grave threats to health and life. Nuclear power plants must be shielded to pro-tect the operators and other personnel from these radiation hazards. The waste products of these power plants must be disposed of with great care. Civilian populations must be in-structed in the hazards of radiological warfare and the means of coping with these hazards.

The term HALF THICKNESS (or half value layer thickness) is commonly used in specifi-cations for materials and structures intended to be used primarily as shields against radia-tion. The half thickness of any substance is the thickness necessary to reduce the intensity

of the given radiation to half. As figure 12C2 shows, the half thickness varies from one shielding substance to another. It also varies with the type of radiation (neutron or gamma) that is under consideration.

12C5. Radiation units

The student of radiation phenomena soon becomes obliged to think in terms of the standard radiation units described in this article.

CURIE. First of all, the student is likely to notice that substances vary widely in the degree of radioactivity they exhibit. If isotope x is more radioactive than isotope y, more x atoms than y atoms will decay in a given time interval. The unit called the curie establishes the activity (that is, the decay rate) of radium as the standard with which the activity of any other substance may be compared.

By using a formula that takes into account the number of atoms per gram and the value of the half life in seconds, scientists have determined that the activity of radium is equal to 3.7×10^{10} nuclear disintegrations per gram per second. This value becomes the unit of comparison.

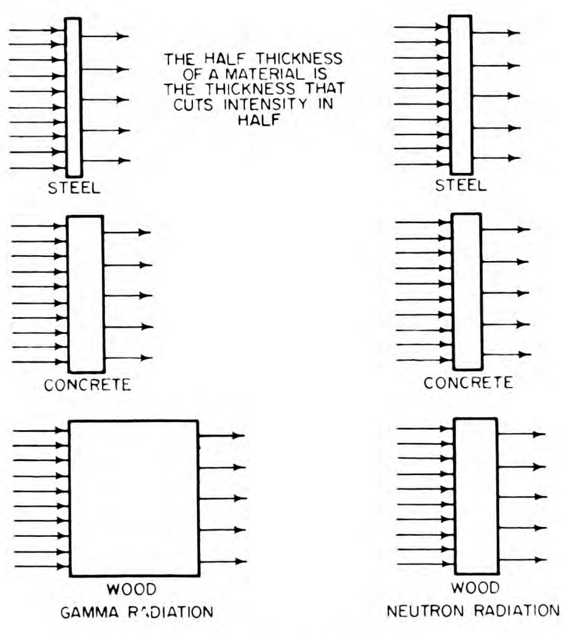

Figure 12C2.—Typical examples of relative half thickness.

A CURIE of ANY radioactive isotope, therefore, is the amount of that isotope that will produce 3.7×10^{10} nuclear disintegrations per second.

In the manufacture of radioactive isotopes for medical and industrial purposes, the curie is often too large a unit for convenient use. Frequently, therefore, the MILLICURIE and even the MICROCURIE are used instead.

At the opposite extreme, the curie is too small a unit for convenient measurement of the high-order activity produced by a nuclear explosion. For this purpose the megacurie (1,000,000 curies) is used.

ROENTGEN. The roentgen was established for the benefit of the medical profession. This unit measures the amount of X-ray dosage given to a patient. Because gamma rays behave like X rays, the roentgen is usable in measuring gamma-ray dosage.

A ROENTGEN is the amount of X or gamma radiation which, in passing through a cubic centimeter of standard air, produces an electrostatic unit (equivalent to 2.083×10^9 of the ion pairs defined in article 12C2.) The absorption of one roentgen by one gram of air results in the release of about 87 ergs (small energy units used in delicate problems in mechanics). This fact will be mentioned again.

In evaluating the effect of radiation on a clinical patient or on a victim of some type of accidental exposure, the radiological expert must know (or at least estimate) the answers to questions like the following: Was the exposure to radiation brief or extended, single or repeated? How many roentgens (or fractions thereof) were received at each exposure? Was the radiation received over the whole body or only on a limited area?

It is impossible, in this brief article, to make a detailed study of the effects of the many possible amounts and combinations of X or gamma radiation dosage. The reader will, however, have a clearer idea of the roentgen if he remembers the following key facts:

1. Twenty-five roentgens or less, received in a single dose and not repeated, have no effect that can be detected by clinical processes.

2. Single doses larger than 25 roentgens (or small, frequent doses amounting to a total of more than 25 roentgens) have increasingly more serious consequences.

3. If the entire body is exposed to 450 roentgens, the chances are 50 to 50 that the victim will die within a month.

4. If the entire body receives 700 or more roentgens, the victim will be almost certain to die.

Some of the doses given in radiation therapy are very small; they are measured in MILLIROENTGENS (1/1,000 roentgen). Other therapeutic doses are very large, but they are directed at a small portion of the body, and therefore destroy few cells except the malignant ones at which they are beamed.

REM. The roentgen, as a unit of radiation dosage, is defined with respect to X and gamma radiation, and should be applied only to those two types. We have seen, however, that alpha and beta particles also initiate ionizing reactions. The various other nuclear particles produced in the laboratory, the reactor, or the exploding nuclear weapon are likewise capable of causing ionization.

The rem is the correct term to use in measuring dosages of these various other ionizing particles. A REM (roentgen equivalent man or mammal) is the quantity of ionizing radiation of ANY type which, when absorbed by man or some other mammal, produces a physiological effect equivalent to that produced by the absorption of one roentgen of X or gamma radiation.

REP. The roentgen measures the strength of the radiation field—the dose to which the patient or victim is exposed. For one reason or another (partial shielding, or variations in penetrative power, for example) the full value of an exposure dose may not always be received by a living organism. Therefore the rep (roentgen equivalent physical) was established to measure the strength of the radiation absorbed within the body.

The rep was originally defined as the absorbed dose of ANY nuclear radiation (gamma rays, beta particles, neutrons, and so on) that would result in the absorption, within animal tissue, of 87 ergs per gram. This figure, as will be recalled, represents the amount of energy released by one roentgen in a gram of air.

Continued experimentation showed, however, that exposure to a dose of one roentgen actually caused animal tissues to absorb more than 87 ergs of energy per gram. After some fluctuation, the value of the rep was defined, as of 1957, as an absorbed dose of 93 ergs per gram of tissue.

RAD. Because the value of the rep was keyed to that of the roentgen and varied as more exact data became available, a need was felt for some INVARIABLE unit of absorbed dosage that would be roughly equivalent to the rep. Accordingly, in 1953, the International Commission on Radiological Units adopted the rad as the desired unit.

A RAD is the absorbed dose of any nuclear radiation that results in the liberation of 100 ergs of energy per gram of absorbing material.

PRACTICAL COMPARISONS. For gamma radiation, which is generally the major threat to health and life, the relationships between the dosage units are simple and easy to remember. For gamma radiation, the exposure dose in rems is approximately equal to the absorbed dose in reps or rads, and for soft tissue this, in turn, is roughly equal to the exposure dose in roentgens. In other words, one can receive 20 rems, reps, or rads without ill effect; he has little chance of recovery if he receives 700 of any of these units.

As the accompanying table shows, however, the rem and the rep are not numerically equivalent for ALL types of nuclear radiation. The student may find this table a convenient means of reviewing, and fixing in his mind, the units he is most likely to meet in further studies of radiation dosage.

Radiation Relationships.

Radiation	roentgen	rem	rep
X-ray	1	1	1
Gamma	1	1	1
Beta	-	1	1
Proton	-	5	1
Alpha	-	20	1
Fast neutron	-	10	1
Slow neutron	-	2	1

12C6. Utilizing ionization phenomena

Much has been said, thus far, about the ill effects of the ionizations produced by nuclear emissions. These same ionizations, however, have been made to serve useful purposes. They have, for example, enabled laboratory scientists to follow and photograph the paths taken by emitted particles. They have also enabled

design engineers to construct a number of radiation detectors for safeguarding personnel and evaluating damage. Only a few examples will be mentioned.

CLOUD CHAMBER. The cloud chamber is one means of showing the traces left by radiation products. (The products themselves are too small and too fast-moving to be shown directly.)

The cloud chamber is essentially a hydraulic cylinder. Before operation, a piston head compresses a volume of gas, saturated with vapor, at one end of the cylinder. When ready to trace emitted particles, the operator quickly moves the cylinder head to enlarge the gas-filled area. He also sends light through the gas. As the gas expands, it cools; the cooling of the intermixed vapor causes visible droplets to collect on any ionized gas particles.

DETECTORS. Most of the radiation detectors in current use are really ion detectors. Many detectors, including the Geiger counter, are characterized by a gas-filled cylinder in which the entering gamma rays (the most penetrating of the three radiation products) ionize the gas molecules. An electrical device in the detector measures and indicates the degree of ionization.

Certain small film-type detectors, however, do not have ionization chambers. Instead, they show directly the effects of beta particles and gamma rays on photographic film.

D. Nuclear Reactions

12D1. Mass-energy relationship

CONVENTIONAL IDEA. Conventional physics has a law of the CONSERVATION OF MATTER. According to this law, the total mass of the material universe remains always the same, regardless of all the rearrangements its component particles undergo. Likewise, conventional physics has a law of the CONSERVATION OF ENERGY. This law states that one form of energy can be converted to another form, but the total amount of energy in the universe neither increases nor decreases.

Mass and energy, to the physicist of the old school, were separate entities, as indeed they appear to be.

EINSTEIN'S IDEA. In the early 1900's Einstein made (and supported mathematically) a revolutionary statement. He said that there is an exact equivalence between mass and energy. Mass can be converted to energy and, conversely and even more strangely, energy can sometimes be converted to mass. (Brief mention of these two types of conversion was made in the paragraphs on gamma radiation in article 12C2.)

According to Einstein, it is not mass or energy as a separate entity, but rather the total mass-energy of the universe, that remains constant. The relationship between mass and energy is expressed in the equation:

$$E = MC^2,$$

where E = energy, in ergs, generated in any reaction;
M = mass, in grams, lost in any reaction;
C = speed of light (3×10^{10} centimeters per second, equivalent to 186,000 miles per second).

CHEMICAL IMPLICATIONS. Even the ordinary chemical processes, Einstein declared, involve the conversion of mass to energy. In order for a chemical reaction to take place, enough energy must be made available, through a conversion of mass, to break the binding forces that have been holding the molecules together.

We have seen that only the electrons in the outermost shells are involved in molecule formation. A comparatively small amount of energy, therefore, is sufficient to free the atoms from one molecular formation and recombine them in another. The mass loss (M) in such a reaction is this small amount of energy (E) divided by the square of the speed of light.

This loss of mass is too minute to be measurable by any laboratory instrument yet devised. For example, the energy produced by the burning of a pound of coal represents a mass loss of 1/3 billionth of a pound. The rest of the coal particles continue to exist as measurable combustion products.

NUCLEAR IMPLICATIONS. As the next article will explain, the forces binding the

tomic nucleus together are vastly stronger ıan the forces binding atoms into a molecule. 'o break these forces, a comparatively large mount of matter must be converted to energy.

Not even the nuclear physicist has succeeded ı converting to energy more than a small raction of any mass large enough to be seen y the unaided eye. In the fissioning of uranium, s in the Hiroshima bomb, about a thousandth art of the total mass of radioactive substance s changed to energy; the remainder is transıuted to fission products.

Nevertheless, fission is a much more effiient source of kinetic energy than combustion. 'igure 12D1 makes some comparisons that peak for themselves.

2D2. Binding energy; mass defect

The protons in an atomic nucleus are all ositive; and one positive charge, as every tudent of basic electricity knows, repels nother. The neutrons, as long as they remain vithin the nucleus, are electrically neutral. Vhy, then, does the nucleus hold together?

For one thing, the neutrons serve as buffers o reduce the effectiveness of the repulsive orces between protons. For another thing, ome natural force, comparable to gravitation ut many times stronger, binds the nucleus nto a unit. This super-gravitational force or 3INDING ENERGY is thought to be similar, in ts effect, to the surface tension that binds a arge number of water molecules into a rainlrop.

The entrance of a new particle into a nucleus, or the exit of a particle from a nucleus, must be accompanied by enough energy to break the binding force; in short, the travelling nuclear particle must act like a small bullet. The energy to break the binding force involves a conversion of mass. The loss of mass by conversion is called the MASS DEFECT.

In nuclear reactions the mass defect, though small, is large enough to be measured by laboratory procedures that are beyond the scope of this chapter. These measurements have shown the truth of a seemingly fantastic statement: with the single exception of ${}_1H^1$, any atomic nucleus weighs less than the sum of the weights of the nucleons composing it; these nucleons lost a small fraction of their mass when they combined.

The binding energy of the nucleus varies from one element to another. The elements in the middle-weight portion of the table of nuclides (fig. 12B5 and 12B6) are most strongly bound together and therefore are least promising as sources of usable energy.

The simple nuclei at the hydrogen end of the table have the lowest binding power. The complex nuclei at the uranium end of the table tend, by virtue of their very complexity, to lack stability; that is why some of them are naturally radioactive. It is the elements at these two extremes of the table that are the most likely sources of usable energy.

Nuclear energy can be released by combining light nuclei to form heavier and more strongly bound ones. This is the process called FUSION.

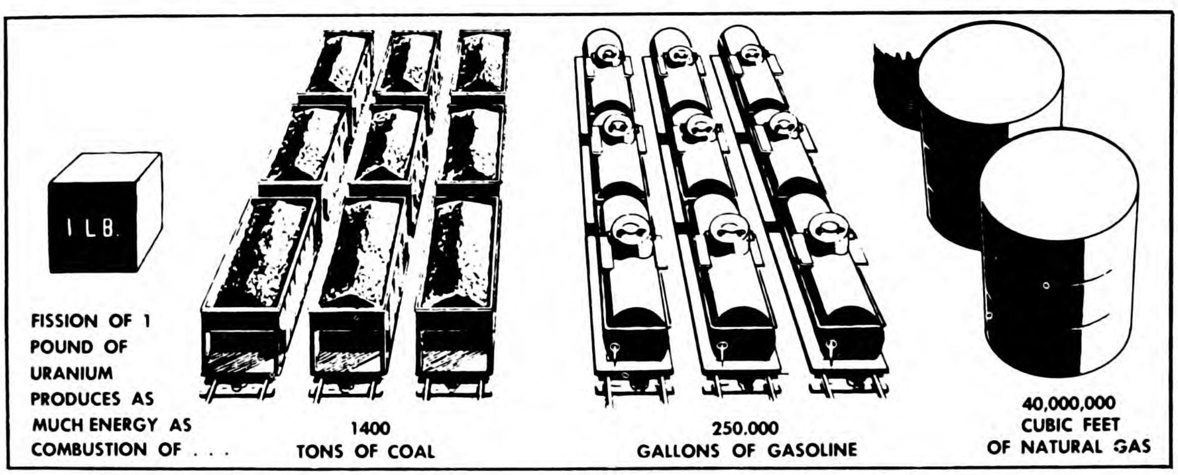

Figure 12D1.—Nuclear energy as compared with chemical energy.

Energy can also be released by splitting heavy nuclei into intermediate (and, again, more strongly bound) ones. This is the process called FISSION. These are the two reactions with which nuclear power engineering is concerned.

12D3. Nuclear fission

PIONEER STAGES. During the late 1930's scientists were conducting several types of "atom-smashing" experiments. One of these experiments involved the use of the neutrons from the deuterium (heavy hydrogen) atom as high-velocity bullets to bombard small quantities of uranium. This experiment produced a result that even the specialists were reluctant to believe until all other possible explanations had been tried and discounted. Some of the uranium atoms had been split into almost equal parts, to form new atoms of barium and krypton.

The physicists could explain this phenomenon in only one way. The heavy uranium nucleus taxes its binding energy almost to the breaking point, much as an oversize dewdrop taxes its surface tension. If all conditions are favorable, a slight, sudden stab against the dewdrop, or the impact of a single neutron against the uranium nucleus, suffices to split either into two nearly equal parts.

The startling experiment was repeated a number of times, and the energy liberated by the reaction was carefully measured. The energy per atom proved to be about 5,000,000 times that of burning coal. Here, then, was a discovery that might have tremendous practical importance, provided the fission reaction could be sustained and controlled.

FISSIONABLE MATERIALS. An intensive search for fissionable materials revealed three substances with practical possibilities as nuclear "fuel." They are as follows:

- U^{235}, a uranium isotope constituting 0.7% of natural uranium,
- Pu^{239}, an artifical isotope of an element plutonium that is itself (for all practical purposes) man-made,
- U^{233}, an artificial isotope of uranium, derived in a reaction involving thorium.

NEUTRON PRODUCTION. Free neutrons are the major tools of the nuclear physicist. They have the proper size and weight to invade the atomic nucleus, and their electrically neutral character keeps them from being repelled by the protons. For large-scale nuclear fission operations, man needs an abundant supply of neutrons.

For laboratory purposes, the physicist can bombard the atoms of a light element (boron or beryllium, for example) with alpha particles or gamma rays from certain radioactive isotopes, or with charged particles from a cyclotron or other accelerator. All these methods result in neutron emission.

In the practical production of radioactive materials, he secures free neutrons by the NUCLEAR REACTIONS THEMSELVES. Studies of radioactive series decay have shown that some fissions result in the freeing of at least one neutron. Under proper control, the free neutrons can be put to work.

CONTROLLING THE NEUTRON. In any nuclear reaction except a planned explosion, both the production rate and the speed rate of free neutrons must be kept under control. This is an essential safety precaution.

When emitted from their atoms, some neutrons travel fast—at about 1/20 the speed of light. For some purposes, such as the splitting of a heavy but firmly bound nuclide like U^{238}, the high kinetic energy of FAST neutrons is required. In other nuclear processes—including the fissioning of unstable heavy nuclides such as U^{233}, U^{235}, and Pu^{239}—a much lower neutron speed is desirable; fast neutrons would simply pass through these nuclides, exciting them but failing to produce fission.

By control methods that will be mentioned shortly, it is possible to decrease the speed of neutrons to about 1/10,000 of the maximum possible value. At this low speed, the kinetic energy of the neutrons is about equal to that of a gas under standard conditions. For this reason they are called THERMAL neutrons.

The term SLOW neutrons includes thermal neutrons, but is much less restricted in meaning.

To slow down fast neutrons, the designers of nuclear reactors use substances or devices called MODERATORS. Good moderating materials are elements from the low end of the table of the nuclides, and compounds formed from these elements. Moderating substances include (but are not limited to) hydrogen, carbon, beryllium, ordinary water, heavy

water (in whose molecule deuterium replaces common hydrogen), and paraffin.

When a free neutron enters a moderator, it collides with (but does not penetrate) one nucleus after another, losing energy with each collision. Eventually it leaves the moderator at a greatly reduced velocity.

Moderating materials can be designed to serve as REFLECTORS. These are layers or structures that turn stray neutrons back toward the parts of the reactor where they will serve a useful purpose.

Substances that allow free neutrons to enter but tend to hold them captive are called ABSORBERS. These substances are used in the safety shields and control rods that are required in all designs for nuclear reactors. If unavoidably present where they are not desired, absorbing substances reduce efficiency.

NEUTRON REACTIONS. Not all emitted neutrons behave alike. Frequently they cause non-fissioning reactions, typical examples of which are sketched in figure 12D2. The moderators and absorbers recently described are deliberately used to produce non-fissioning reactions. It is possible, however, for such reactions to occur even within fissionable substances.

In ELASTIC SCATTER (also called ELASTIC COLLISION) a neutron or other particle touches or nearly touches the target nucleus, then bounces away. No nuclear energy is released, though the colliding particle may transfer some of its kinetic energy to the nucleus.

In INELASTIC SCATTER, part of the energy of the collision EXCITES the target nucleus and causes it to give off gamma radiation. The bombarding particle may merely touch the target nucleus, or it may actually pass through it as shown in the central part of figure 12D2.

The reaction called PARTICLE EJECTION ON BOMBARDMENT resembles inelastic scatter, with the difference that one particle enters the nucleus and a different particle leaves it. Gamma radiation accompanies this reaction.

In CAPTURE a neutron (or, rarely, some other particle) enters the target nucleus and stays there. This reaction, once again, excites the target nucleus and produces gamma radiation. By the capture of a neutron, the nucleus changes from one isotope to another.

When the bombarding particle splits the target nucleus into two smaller nuclei, as shown in figure 12D3, the reaction is, of course, FISSION. Though omitted from this drawing for the sake of simplicity, the planetary electrons of the fissioning nucleus are divided between the product nuclei when the new atoms are formed. The result, then, is the production of two lighter and often more stable atoms.

Since fissionable substances have a high ratio of neutrons to protons, their transmutation to medium-weight substances is usually accompanied by the liberation of at least one

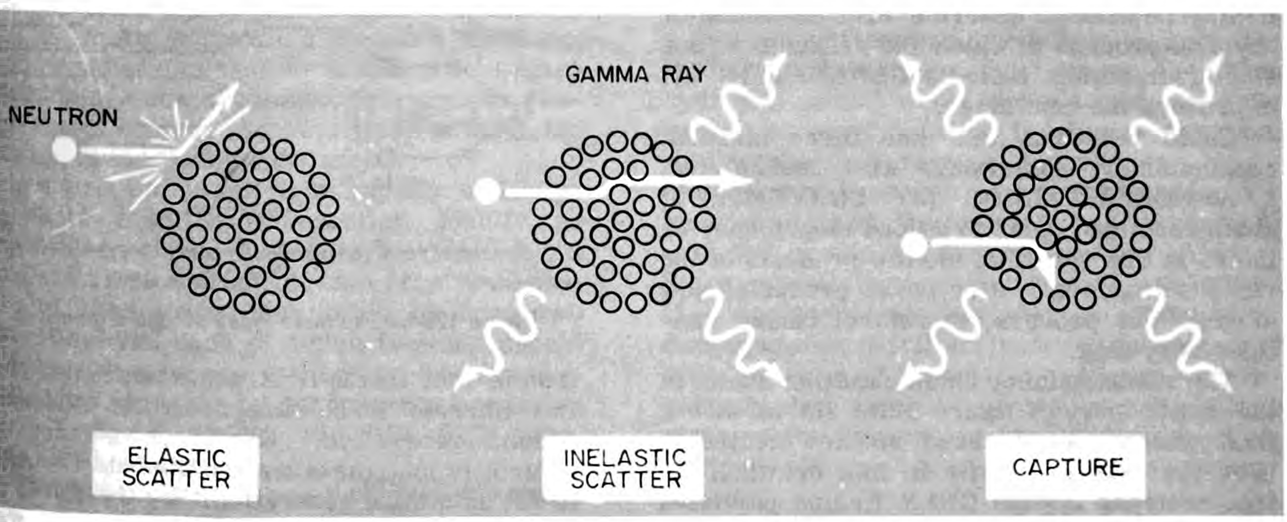

Figure 12D2.—Some non-fissioning reactions.

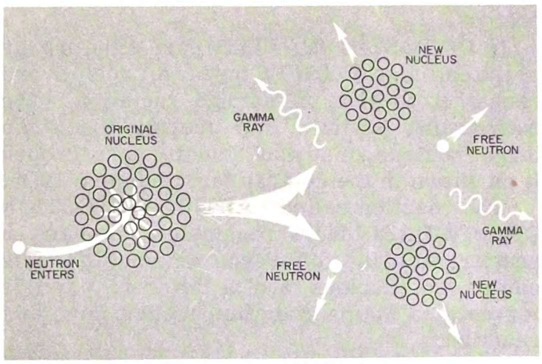

Figure 12D3.—A representative fission reaction.

spare neutron. This neutron is welcomed by the physicist, for it becomes a tool for possible use in producing the NEXT fission. It is the emission of free neutrons that makes possible a self-sustaining chain reaction.

CHAIN REACTIONS. The two neutrons liberated by fissioning in figure 12D3 may behave in any of the various ways that have just been summarized. If conditions are especially favorable to fissioning, they may both produce fissions. Under slightly different conditions, one may cause fissioning and one may be captured. As long as any fissioning reaction can be traced back, step by step, to the original fission, the process is a CHAIN REACTION.

The term CHAIN REACTION is not the exclusive property of the nuclear physicist. It may be used to describe ANY chemical or physical process in which the products of one stage (sometimes called a GENERATION) act to produce the next stage.

Chain reactions fall into three classes: nonsustaining, sustaining, and multiplying.

A NONSUSTAINING (or CONVERGENT) chain reaction comes to a dead stop sooner or later. In this reaction, too few products of the various stages are effective in producing new stages. The process, therefore, cannot continue very long.

The nonsustaining chain reaction shown in the upper part of figure 12D4 starts with a first generation of three emitted neutrons. (For the sake of clarity in this drawing, the free neutrons are the ONLY fission particles shown; the presence of all the other fission products is to be taken for granted.) One neutron is lost in the first generation; the other two liberate three new neutrons to form a second generation. One second-generation neutron is lost; the other two liberate two more to act as a third generation. By the end of the fifth generation, no neutrons remain to start new fissions. Therefore the reaction ends.

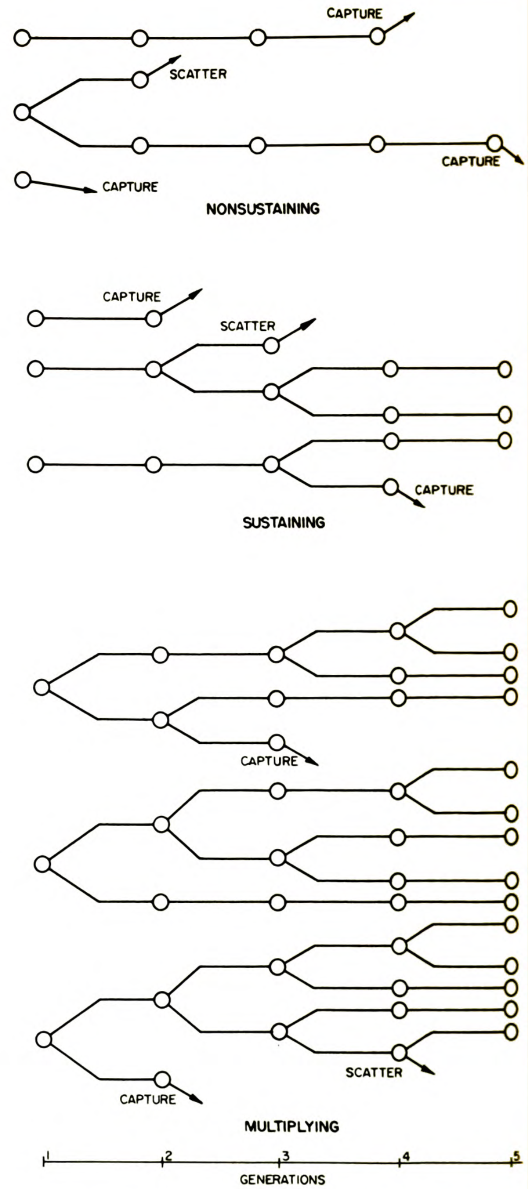

Figure 12D4.—The three types of chain reactions.

In a SUSTAINING (or STATIONARY) reaction the gains by new fissions exactly balance the various types of losses. Consequently, as shown in the central part of figure 12D4, the reaction continues at a constant strength.

The lower part of figure 12D4 shows a MULTIPLYING (or DIVERGENT) chain reaction. In each generation, the reaction products (in this instance, free neutrons) that are gained exceed those that are lost. If conditions were especially favorable, the ratio of gains to losses would be still higher.

The nature of any nuclear chain reaction depends, in part, on the purity of the fissionable material used. Impurities cause more neutrons to be lost through scatter or capture.

The nature of the reaction also depends, in part, on the mass and shape of the fissionable material. Even for highly refined fissionable substances, there are limits below which there are too few atoms to support a chain reaction. This brings us to the problem of CRITICALITY.

A mass (in a given shape) that is just great enough to support a sustaining chain reaction is called a CRITICAL mass. A SUBCRITICAL (smaller than critical) mass will support only a nonsustaining chain reaction. A SUPERCRITICAL mass will support a multiplying chain reaction.

FISSION BOMB POSSIBILITIES. As a very necessary safety precaution, the masses of fissionable material present in a nuclear bomb must be kept subcritical until time for the bomb to be detonated. Then a supercritical mass must be formed very rapidly. One way of producing a supercritical mass is by forcing two or more subcritical masses together. Another way is to squeeze a subcritical mass tightly into a new shape and/or a greater density that becomes supercritical without the addition of any more substance.

In a weapon, an efficient, rapidly multiplying chain reaction is essential. Ideally, no free neutron should be lost to the process. If the first fission produced two free neutrons, each of these neutrons should produce two more fissions, each of which fissions should liberate two neutrons, and so on. The fissions would then increase by geometric progression (1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, and so on).

The eighty-first step of this process results in 2.5×10^{24} fissions—enough to transmute a kilogram of refined uranium. The time required for the 81 steps is $1/10^8$ second. These are the types of numbers that had to be considered in the design of the Hiroshima bomb.

UTILIZING SUSTAINING REACTIONS. When "atomic fuel" is used to produce power—as in some ships now in commission, other ships under construction, and certain experimental electric plants ashore—a sustaining type of chain reaction is required. Neutron production must not be allowed to get out of control; neither must it be allowed to die out.

The designers of nuclear reactors must face and solve many problems related to the production of an efficient, controllable chain reaction. These problems are beyond the scope of this chapter, but are discussed in texts on nuclear power engineering.

Other problems center about the safety factors—both for the equipment itself and for the people who operate it or live near it. Even the disposal of waste products must be carefully planned to avoid present and future dangers.

12D4. Nuclear fusion

As briefly mentioned before, fusion is the merging of two light nuclei to form a heavier one, with an accompanying conversion of mass to energy. For reasons that will be mentioned soon, fusion reactions are often called THERMONUCLEAR reactions.

SUITABLE SUBSTANCES. In order to fuse, two nuclei must come very close together with enough kinetic energy to break the binding force of one of the nuclei. Because protons repel one another, thus tending to keep the nuclei containing them apart, the single-proton hydrogen nuclei would seem to be the most promising materials for the fusion reaction.

Because they have no neutrons, two atoms of ordinary hydrogen cannot fuse to form a heavier element. Deuterium or heavy hydrogen, with one proton and one neutron per atom, is more promising. Experiments have shown that two atoms of deuterium can fuse, producing an atom of tritium (radioactive hydrogen) plus an atom of ordinary hydrogen. Alternatively, two atoms of deuterium can react to produce the helium isotope $_2He^3$ plus a free neutron. Either reaction liberates nuclear energy.

Any tritium produced by fusion can react with deuterium to produce the helium isotope

$_2He^4$ plus a free neutron. This reaction again releases nuclear energy.

Deuterium, then, is an effective source of energy, provided it can be made to fuse at all. To achieve fusion, a very high value of kinetic energy must be expended in forcing any two deuterium nuclei to unite. In laboratory experiments, artificial acceleration of nuclear particles has produced enough energy to initiate small-scale fusion reactions. Mechanical acceleration of particles, however, is not feasible in nuclear weapons, nor is it adaptable to industrial energy production.

Thus far, heat has proved to be the only form of kinetic energy capable of initiating a fusion reaction large enough to have practical applications. Temperatures comparable to that of the sun—millions of degrees Centigrade—are required. A multiplying fission chain reaction produces these temperatures. Naturally the container is vaporized by the reaction; this is suitable for a weapon, but not for an industrial power plant.

Fusion weapons, then, are really fission-fusion weapons, in which fission occurs first and acts to trigger the still greater fusion reaction. Because heat provides the kinetic energy necessary for their functioning, fusion weapons are sometimes called THERMONUCLEAR weapons.

FUSION AND FISSION COMPARED. Both fusion and fission liberate nuclear energy. The two reactions differ in several respects.

One respect, THE MEANS OF INITIATION, has already been discussed. Fission results when a supercritical mass of suitable heavy material is rapidly formed. The reaction occurs automatically as soon as the free neutrons, already present in the fissionable material, are supplied with a large enough number of atoms to support the process. Fusion does not occur automatically; it must be initiated by the application of extremely high kinetic energy to suitable light substances—namely, deuterium and tritium.

There is a practical limit to the SIZE of a fission weapon and, therefore, to the amount of energy that can be released by this reaction. If a weapon contains more than a limited number of subcritical masses of fissionable material, it becomes unsafe to handle and transport. No such limit is placed on the amount of heavy hydrogen a fusion weapon can contain; this weapon may be as large as the available launching devices permit. Much greater destruction, therefore, is possible with fusion weapons.

Fission produces a large number of RADIOACTIVE PRODUCTS—gamma rays, nuclear particles, and isotopes of various middle-weight elements. Some isotopes decay in a short time. Others have a long half life and can remain dangerous for a comparatively long time. A few long-lived isotopes, including strontium^{90}, tend, if they enter the body at all, to become lodged in the bones. There they can cause radiation damage over a period of years. Fusion, on the other hand, has tritium as its only radioactive product, and the tritium is itself fused with deuterium to produce stable helium.

12D5. Other nuclear reactions

Under laboratory conditions, particles other than neutrons have been (and still are) used to bombard atomic nuclei. Normally a very high concentration of energy is required to force one of these charged particles into a target nucleus.

Alpha particles, protons, deuterons, gamma rays, and beta particles can all produce transmutations.

ALPHA-PARTICLE bombardments produce stable isotopes plus protons or, alternatively, unstable isotopes plus neutrons.

PROTONS sometimes produce transmutations accompanied by the emission of neutrons, deuterons, alpha particles, and gamma rays.

DEUTERON-produced transmutations are accompanied by emissions of neutrons, protons, or gamma rays.

GAMMA RAYS are useful in releasing neutrons from light-element nuclides.

When captured by a nucleus, a BETA PARTICLE causes an X ray to be emitted.

Some, or perhaps all, of these reactions may take place during a complicated, high-energy process such as the explosion of a fission weapon.

CHAPTER 13

PRINCIPLES OF NUCLEAR WEAPONS

A. Introduction

13A1. Scope

Nuclear weapons are sometimes called SPECIAL weapons, the name by which they were identified in early non-classified documents.

This chapter will deal with hypothetical fission and fusion weapons, and will make some comparisons between the two types. It should be clearly understood that the chapter makes no pretense of describing specific marks and mods of nuclear ordnance. The emphasis is on underlying principles, not on design details and operational sequences. The reader will find, however, that an understanding of the background information in this chapter is necessary to any of the more specific studies of nuclear ordnance he may make in the future.

Like the assembled weapons, the fuzes and other non-nuclear components will be discussed without reference to specific service designs.

The latter portion of the chapter takes up some of the problems related to the use and handling of nuclear weapons.

13A2. Importance

The Navy has a wide variety of officer billets. Many of these billets are somewhat indirectly related to weaponry. All officer billets, however, are concerned with security, safety, defensive measures, and, when necessary, disaster relief. All these officer responsibilities are graver and more complex, now that nuclear warfare has become possible. Whether or not he expects ever to be directly in charge of any phase of the nuclear weapons program, every young officer needs such information as he will find in this chapter and in other non-classified summaries.

B. Fission Weapons

13B1. General requirements

FISSIONABLE MATERIAL. As mentioned in chapter 12, fissionable material for use in weapons consists of suitable isotopes of uranium and plutonium. When a mass of one of these isotopes—supercritical in size and shape—is very rapidly formed, a high-order multiplying chain reaction automatically begins. If all design features permit this reaction to continue in accordance with the laws of geometric progression, a powerful explosion occurs.

If the design features do NOT favor a rapidly multiplying chain reaction, the fission will produce only a low-order explosion; the weapon may even be a complete dud. In view of the high cost of fissionable materials and the military importance of the targets at which fission weapons are directed, it is important that these weapons perform reliably. This section will discuss some of the practical problems that have been met and solved by the designers of fission weapons.

SAFETY FEATURES. A fission weapon requires a device (or system of devices) to prevent a supercritical mass from forming prematurely or accidentally. Tragic results have followed the infrequent premature detonations of conventional weapons. Large-scale destruction would follow the premature detonation of a nuclear weapon.

It is, therefore, extremely important that every nuclear weapon be so designed and assembled that it will remain unarmed until the ordered conditions for arming have all been met. Section E, on fuzing techniques, will mention this topic again.

CONFINING THE REACTION. Obviously a nuclear explosion cannot be confined very long; the shock and heat of the reaction would soon overtax the resistance of even the strongest container. Yet the reaction MUST be confined until it has gained so much momentum that it cannot be stopped short of a full-scale explosion.

If the nuclear reaction were not confined during its early stages, the supercritical

mass would tend to fly apart, breaking into a number of subcritical masses.

One way to confine the reaction would be to make the outer case of the nuclear weapon abnormally thick and heavy. An equally effective arrangement, however, is to place the explosive elements within an inert but comparatively small inner container known as a TAMPER. The tamper need not have great tensile strength, but it must be a very dense substance. Information on the actual substances currently used is beyond the scope of this chapter.

In addition to its primary function of confining the nuclear reaction during its early stages, the tamper may also act as a REFLECTOR. If made of (or lined with) a reflecting substance, it will deflect stray neutrons back into the reaction, thus increasing the efficiency of the weapon.

ACHIEVING SUPERCRITICAL MASS. The subcritical mass or group of masses must be changed to a supercritical mass almost instantaneously. (Mathematical computations beyond the scope of this article set the maximum allowable time at less than 10^{-6} second.)

Too great a lapse of time in the formation of the supercritical mass might have one or the other of two undesirable results.

1. A continuing reaction, rather than a multiplying one, might be initiated. The heat generated by this reaction would be likely to melt enough of the fissionable material to return the mass to a subcritical state.

2. An inefficient multiplying reaction might begin and continue until it produced a low-order explosion.

Two means of achieving a supercritical mass will be discussed in the next two articles.

13B2. Gun principle

The hypothetical nuclear weapon sketched in cross section in figure 13B1 contains two subcritical hemispheres of a suitable isotope of uranium, with their plane surfaces facing each other across an air gap.

If the intervening gap is very rapidly closed, the two hemispheres will unite to form a perfect sphere. This shape, by reason of its volume-to-surface ratio, is the configuration most favorable to a multiplying chain reaction, for it gives neutrons the least possible chance to escape. The masses of the

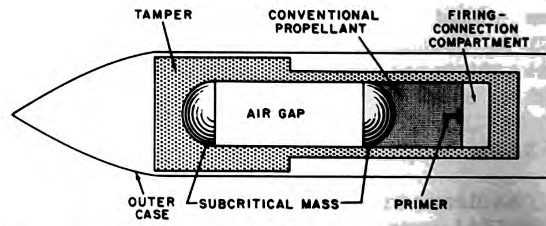

Figure 13B1.—A hypothetical gun-type fission weapon.

hemispheres are such that, when combined, they will constitute a supercritical mass.

Union of the two hemispheres is achieved by shooting one at the other, as a conventional gun shoots a projectile at a target. The hemisphere at the right is the projectile; the one at the left is the target. As in a gun, a firing mechanism and a primer initiate the propelling action.

Notice that the fissionable material occupies a comparatively small part of the interior of the weapon. The tamper is comparatively large.

13B3. Implosion principle

A single subcritical mass of fissionable material can be made supercritical by compressing it forcibly and rapidly. If the applied pressure is strong, and is equally distributed around the entire surface of the fissionable material, the space between atoms can be significantly reduced, with the result that fewer neutrons have a chance to become lost to the chain reaction. This is the principle behind the implosion type of fission weapon.

Uranium and plutonium are among the heaviest elements. To squeeze them effectively during the very brief time that is allowed, the compressive force must be an extremely powerful one. Conventional high explosives, if properly arranged and detonated, can furnish a shock wave that meets the requirements.

Figure 13B2 represents a cross section of the payload in a purely hypothetical implosion-type fission weapon. At the center is a sphere of fissionable material, either uranium or plutonium. Completely surrounding the sphere is a charge of conventional high explosive. A firing system provides for the SIMULTANEOUS detonation of the entire outer surface of the hollow sphere of conventional high explosive.

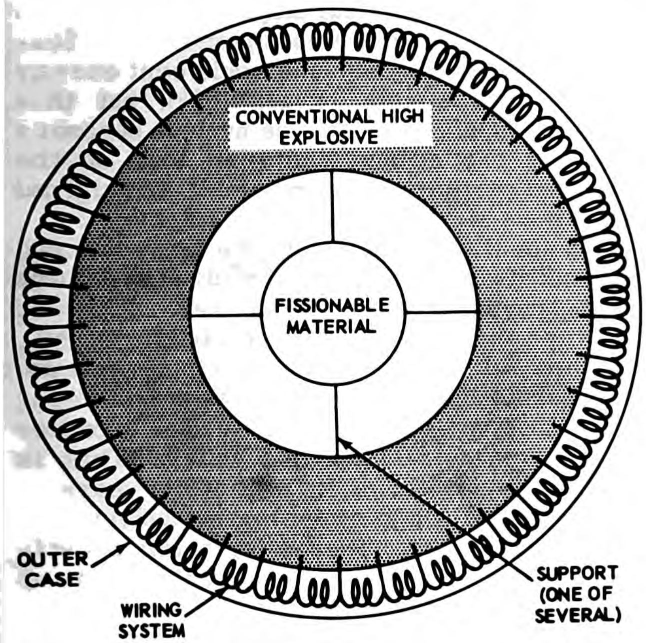

Figure 13B2.—Cross section of the explosive chamber in a hypothetical implosion weapon.

When the conventional explosive is detonated, a smooth shock wave moves inward against the sphere of fissionable material, striking it with equal force at all points. As a result of this suddenly applied squeezing force, the density of the plutonium is increased sufficiently to make the mass supercritical. A multiplying chain reaction atuomatically begins.

13B4. Neutron sources

A question may arise as to the origin of the first generation of free neutrons in a fission weapon.

One source is the air trapped within the weapon. Air always contains free neutrons, probably as a result of cosmic-ray reactions with its nitrogen and oxygen atoms.

Another neutron source is the uranium or plutonium as originally assembled in the weapon. Even in subcritical masses, these radioactive substances undergo a small amount of spontaneous fission that results in the production of stray neutrons.

The designer of a nuclear weapon, however, wishes to be absolutely certain that an abundance of neutrons will be available for use as soon as the supercritical mass is achieved. Therefore he places, in or near the fissionable material, a special capsule called the INITIATOR.

The initiator contains two substances. One substance is a reliable alpha-particle emitter such as radium or radon; the other is a light element such as beryllium. The light element, when subjected to alpha bombardment, will emit neutrons. The enclosing capsule is carefully designed to prevent any premature neutron development.

The same mechanical impulse that forms the supercritical mass shatters the initiator and makes emitted neutrons available to start the chain reaction.

C. Fusion Weapons

13C1. Preliminary

As chapter 12 explained, nuclear energy is released not only by the splitting of heavy nuclei (the fission reaction) but also by the joining of light nuclei to form heavier ones (the fusion reaction).

The light nuclei at the hydrogen end of the table of nuclides (fig. 12B5) have lower binding energies than uranium and plutonium. Upon hearing this statement for the first time, one might question quite justifiably why fusion weapons were not developed first. The reasons are several; but the main reason is the amount of initiating energy required.

ENERGY REQUIREMENTS. Neutrons, the tools used in producing large-scale fission reactions, possess the advantage of electrical neutrality. To cause fission, a free neutron has to pierce the binding energy of a heavy nucleus that is already in unstable equilibrium, but it does not have to overcome any electrostatic repulsion.

When two light nuclei fuse to form a new and heavier nucleus, however, at least two mutually repellant protons are involved. One proton is in the nucleus that (for the sake of simplicity) we can regard as the target; the other is in the nucleus that we can regard as the projectile. The projectile nucleus must be impelled with enough kinetic energy to pierce

the binding energy of the target, in spite of the repulsive forces that act between the two protons or sets of protons.

The energy requirements do not have to be guessed; for the various combinations of target and projectile nuclei, they can be computed by standard formulas of nuclear physics. When the United States began in earnest to develop a nuclear weapon, the fusion reaction was ruled out as being unlikely of achievement, on a practical scale, by any means available to man. After fission detonations had been achieved and their effects had been studied, however, the physicists began to suspect that the thermal energy released by a fission reaction might possibly be adequate to start a fusion detonation.

A fission explosion reproduces—briefly and in small space—intensities of light and heat comparable to those in the sun. A fusion explosion does still more; it duplicates a part of the actual process by which the sun and OTHER stars produce their light and heat. This process is not a chemical burning reaction; it is a nuclear fusion reaction in which four nuclei of simple hydrogen become one nucleus of stable helium, with a conversion of mass to radiant energy. The next article will summarize the solar cycle.

SOLAR FUSION CYCLE. Man has reproduced—on small scale under laboratory conditions—the six-stage process by which, according to the currently accepted theory, the sun "burns hydrogen as fuel." The process involves carbon, which undergoes a series of transmutations as it captures one proton (hydrogen nucleus) after another, then suddenly emits all the captured hydrogen (now fused into a single helium nucleus) and regains its original identity. Figure 13C1 shows the sun's continuously repeated cycle.

In the first stage simple carbon (C^{12}) fuses with hydrogen (H^1), with an accompanying release of radiant energy representing the mass lost in the fusion. A similar fusion and release of energy take place in the third and fourth stages. In the second and again in the fifth stage, the constantly growing nucleus emits a positive electron; this means, in each instance, that an excess negative charge remains on the nucleus and, in effect, converts a captured proton to a neutron by counterbalancing its positive charge.

In the sixth and final stage a fourth proton is captured. If the previous pattern were followed, the growing nucleus would emit energy and become simple oxygen (O^{16}); but this doesn't happen. Instead, the nucleus becomes violently excited and emits all four of the captured particles, thus regaining its original identity as simple carbon.

By the time of emission, the four captured protons (two of which, as already noted, have been converted to neutrons) have achieved identity as an alpha particle (article 12B6), which is, of course, simply a helium nucleus. The carbon has merely acted as a catalyzing agent to bring four hydrogen nuclei together and hasten their fusion into helium. This is the cycle by which, for its millions of years of existence, the sun has been heating and lighting our solar system. The astrophysicists estimate that enough hydrogen remains to keep the cycle going for ten billion more years.

13C2. Fusionable materials

CHOICE. In the sun, then, hydrogen and carbon nuclei take part in a revolving, self-perpetuating process in which carbon becomes nitrogen and oxygen isotopes, and then reverts to carbon when all the captured hydrogen fuses into helium. In designing the first fusion weapon, the physicists decided against trying to reproduce the carbon-hydrogen cycle.

The reason was a practical one. Though not complex, the carbon, nitrogen, and oxygen nuclei involved in this cycle have higher binding energies than the two hydrogen isotopes deuterium (${}_1H^2$) and tritium (${}_1H^3$). Since the problem of supplying adequate initiating energy was known to be difficult at best, it seemed wise to choose the simplest reagents possible. The reagents must have both neutrons and protons; this requirement ruled out ordinary hydrogen, but not deuterium and tritium.

PRACTICAL FUSION REACTIONS. As mentioned briefly in chapter 12, two deuterium nuclei can fuse in either of two ways, as follows:

$${}_1H^2 + {}_1H^2 \longrightarrow {}_1H^1 + {}_1H^3 + \text{energy, and}$$

$${}_1H^2 + {}_1H^2 \longrightarrow {}_2He^3 + \text{neutron} + \text{energy.}$$

A fusion weapon can, then, be based on deuterium. The tritium produced in one of the

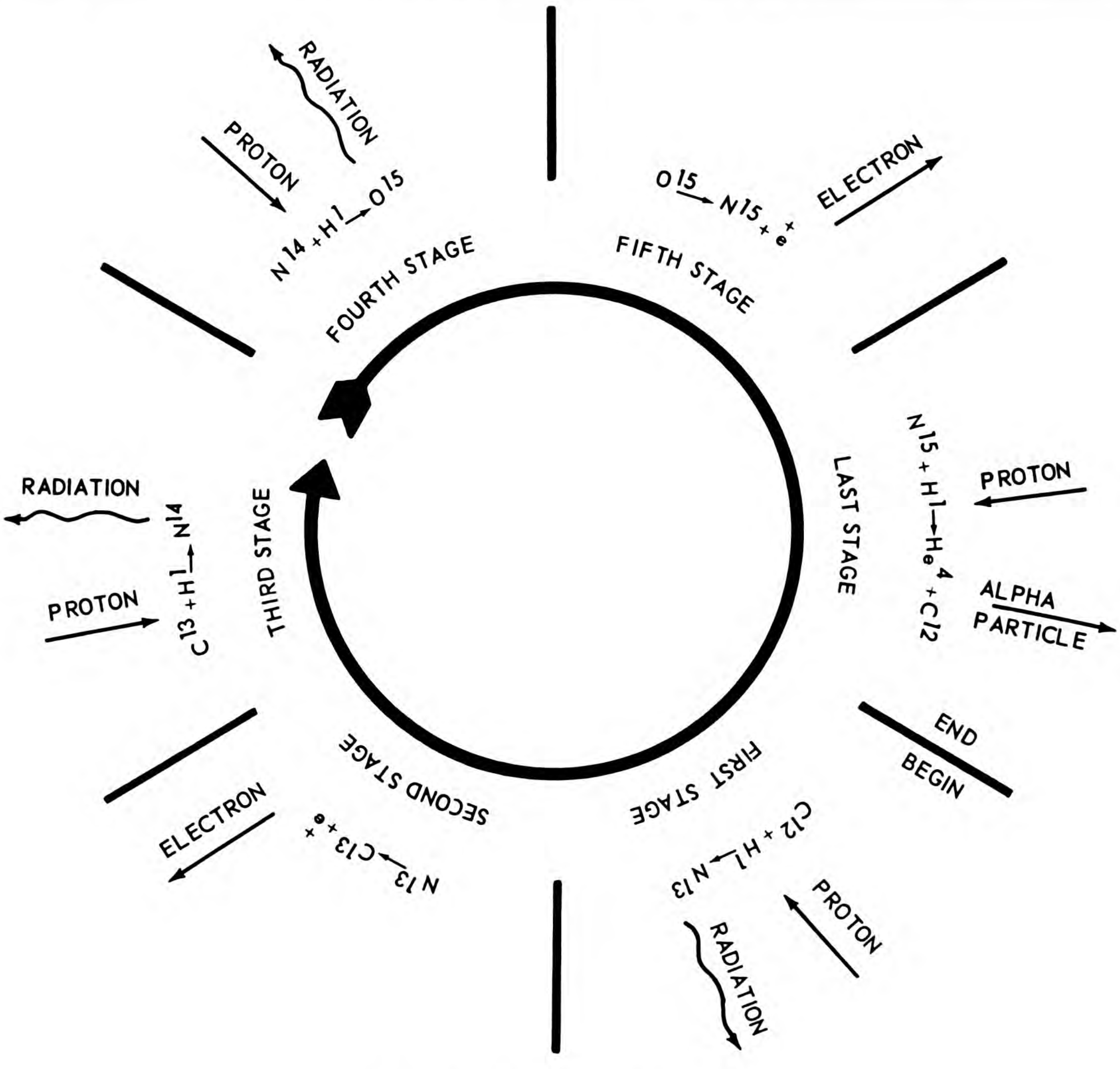

Figure 13C1.–Fusion in the sun.

two possible deuterium fusion reactions is the radioactive hydrogen isotope identified as H3 in figure 12B5. It does not become an end product, but rather enters into the fusion reaction by combining with deuterium, as follows:

$$_1H^2 + {}_1H^3 \longrightarrow {}_2He^4 + \text{neutron} + \text{energy}.$$

In the fusion weapon, then, as in the sun, hydrogen becomes helium, with a release of energy.

As a fusion reaction progresses and the heat intensifies, other nuclear reactions may (and sometimes do) take place. It is possible, for example, for the neutrons liberated during fusion to cause various fissions that would be unlikely to occur at lower temperatures.

Because it is usable from the beginning of the fusion process, tritium as well as deuterium may be included in the payload of a fusion weapon.

13C3. Fusion weapon characteristics

As chapter 12 briefly mentioned, a fusion weapon (sometimes called a thermonuclear weapon and popularly known as an H-bomb) is a fission-fusion device.

SEQUENCE OF EVENTS. The first explosive action in a fusion weapon is the detonation of a conventional high explosive or the burning of a conventional propellant. As a result, the mass of uranium or plutonium becomes supercritical. Fission spontaneously begins. When the heat of fission becomes high enough, fusion of the deuterium (or deuterium and tritium) nuclei begins. As fusion progresses, certain neutrons that first appeared to be byproducts may be drawn into the explosive process.

D. Weapon Comparisons

13D1. Size

In the years since Hiroshima, means have been found to reduce the size and streamline the exteriors of fission weapons. There is, however, no nuclear equivalent of the hand grenade or the bazooka—nor is there likely to be, except in the comic strips.

A fission weapon must contain enough fissionable material to produce a supercritical mass, and enough ancillary material to keep the weapon from flying apart too soon. These requirements are likely to keep fission weapons permanently outside the minor-caliber classification.

According to present knowledge of FUSION, it will not occur at all, on a practical scale, unless it is triggered by a fission reaction. A fusion weapon, therefore, meets all the size and weight requirements of at least a minimum fission weapon. In addition, it must have space for a fusionable payload and strength to confine the fusionable material until an extremely high temperature is reached.

13D2. Yields

FISSION. There are practical limits to the amount of subcritical material that can be placed in a single fission weapon.

If an implosion weapon contains a mass that is very nearly critical, or if a gun-type weapon contains subcritical masses in excess of certain size and weight combinations, that weapon becomes unsafe to store and handle. There is always the consideration that some accident or incident may occur, during normal shipping and handling, to produce criticality and start a premature detonation.

The premature reaction might be a flash rather than a full-scale detonation. Even this, however, would be a catastrophe. If it failed to kill nearby personnel immediately, it would nevertheless subject them to a fatal dose of ionizing radiation. It might contaminate the area with fission products. News of the accident would tend to lower the military and civilian morale throughout the nation.

Therefore fission weapons, by their nature and for reasons of safety, are limited as to the amount of fissionable material they contain. Consequently they are likewise limited as to the size of the explosion each can produce.

FUSION. Since a multiplying fission reaction is used as the fusion trigger, even a "small" fusion explosion is large in comparison with any other type. Furthermore, in theory at least, there is no upper limit to the size of a fusion reaction. A large amount of deuterium or deuterium-tritium is no easier to detonate, and no more susceptible to accidental actuation, than a small one. Actually, then, the size and weight of a fusion weapon need not be limited by the peculiar properties of its fusionable payload.

Its size and weight are likely, however, to be restricted by other factors—such, for example, as the facilities for handling and launching. Another limiting factor might be called military judgment. Using a bomb that "overdestroys" a target has no merit in itself.

The fact that nuclear weapons, and particularly fusion weapons, may (and under some conditions probably will) be used in combat has caused the military planners to revise many earlier concepts of strategy and tactics.

13D3. Radioactivity

FISSION. All fission reactions practicable in ordnance require radioactive materials and scatter large amounts and varieties of radioactive products. As chapter 12 explained, the various radioactive byproducts vary in half life from a few seconds to many years. All these byproducts are hazardous until they have decayed to negligible amounts.

FUSION. On the other hand, the fusion reaction, as such, produces only one radioactive isotope; namely, the tritium that is consumed in the reaction. Of course the fission that triggers the fusion produces radioactive isotopes, as always. Since the area covered by a fusion explosion is comparatively large, however, the radioactive contamination is spread out widely and thereby diluted, unless additional and unusual fissions occur.

One of the current problems of scientists and ordnance engineers is the development of "cleaner" nuclear weapons that will accomplish military objectives without widespread radiation hazards. In event of nuclear warfare, it is probable that fission weapons will be used over our own territory. An example would be the use of nuclear war heads in missiles to destroy attacking enemy aircraft. It is also certain that windborne radioactive products will be carried across national boundaries. It is, therefore, important that the incidental contamination be reduced as much as possible.

E. Fuzing Techniques

13E1. Introduction

In the hypothetical nuclear weapons described in this chapter, a conventional explosive reaction always acts as the trigger. This is followed by the fission and finally (if arranged for) the fusion reactions. Actually, then, the problem of fuzing a nuclear weapon is similar to the problem of fuzing conventional bomb-type or gun-type ammunition. The techniques may be somewhat more sophisticated, but the essential fuze components—arming system, detonator, safety arrangements, and so on—are all present.

A nuclear weapon may be designed to explode in the air, at the surface of the ground or water, or below one or the other of these surfaces. These considerations affect the choice of a fuze.

13E2. Fuzing for air burst

Heavy blast damage to a target area is frequently the most effective means of gaining a military objective. As chapter 14 will explain, a nuclear detonation in the air above a target produces widespread blast effects. Several types of fuzes can be used to initiate a detonation at a selected altitude.

RADAR TYPE. A fuze may be constructed to operate much like a small radar. It may transmit, receive, and compare electromagnetic pulses, and may fire when the signal (or combination of signals) meets specific built-in requirements.

The forerunner of current radar-type fuzes was the proximity (or VT) projectile fuze of World War II. Because recent years have seen many improvements in electronic equipment, radar-type fuzes are likely to be used extensively in the future.

BAROMETRIC TYPE. As the reader will recall from earlier studies in basic sciences, the atmosphere exerts pressure. Like water pressure, atmospheric pressure increases with depth. The barometric switch (familiarly called the BARO) is a fuzing device that responds to a predetermined value of atmospheric pressure.

The barometric initiating device has no exact counterpart in older bomb-type weapons. It corresponds roughly, however, to the conventional hydrostats that are used in underwater ordnance.

TIMER. Mechanical timing devices, representing various applications of the clock principle, are used in many conventional projectiles, bombs, and mines. Not all of these older clock mechanisms are used to cause firing at a preselected instant. Some are used, instead, to prevent firing from occurring BEFORE a given instant; these timers are associated with impact or influence devices that initiate the actual firing.

In an aircraft-launched nuclear weapon, of course, safety delays are vitally important to protect the launching craft and personnel. A timer can be designed to provide these delays, and also to close the firing circuit when the bomb has fallen a selected distance below the launching altitude. The dropping speeds of the various types of nuclear bombs are known; therefore the dropping distance is easily converted to an equivalent time interval.

13E3. Fuzing for surface burst

A nuclear weapon, like a conventional one, may be designed to burst at the surface of the ground or water. An impact fuze, in which the shock of landing causes one operating component (or group of components) to move with respect to another, is used for surface bursts.

If a delayed explosion is desired, an impact fuze may contain a timing device that prevents the detonation from occurring immediately upon impact. A heavy weapon, falling from a high altitude, will penetrate some types of soil and may even bury itself. A delayed-action fuze permits this burial to take place.

13E4. Fuzing for underwater burst

Nuclear weapons, like conventional ones, are capable of underwater detonation by hydrostatic fuzes. Timing devices can also be used to produce underwater detonations.

13E5. Safety devices

Because of the high destructive capacity of all nuclear weapons, the fuzes used in them must have positive protection against accidental or premature arming. Certain types of safety arrangements and accessories have performed reliably in conventional weapons. With adaptations and refinements, similar safety devices are usable in nuclear weapons.

ARMING WIRES. The arming wire has long been familiar to naval aviators. This wire is threaded through a fuze to keep a movable component from taking its armed position. During launching, the fuzes (or equivalent devices) are freed from the arming wires.

In conventional aircraft bombs a delay period, provided by a windmill-type vane and a gear train, keeps the fuze from becoming armed immediately after the arming wire has been removed. In the safe interval, the planting craft escapes from the danger zone.

OTHER SAFETY FEATURES. Inertia, as the reader will recall from basic physics, is the natural tendency of a material object (if stationary) to resist being set in motion and (if moving) to resist any change in the direction or speed of motion. In weapons, the force of inertia can be utilized to produce a safety delay by retarding the relative motion between two components.

During the acceleration of a projectile in a gun barrel, inertia tends to force all parts of the fuze mechanism toward the rear. This manifestation of inertia—called SETBACK in gunnery—can be used to delay arming. Similarly, in several types of mine accessories and components, inertia is used either to prevent an undesired action or to cause a desired one.

Some fuzing arrangements for nuclear weapons use inertia as a means of achieving a safety delay.

Electrical arrangements constitute another means of assuring safety before and during launching, and for a selected period thereafter. Nearly all naval mines, for example, are assembled and planted with several breaks in the battery-to-detonator circuit. Each break consists of a normally open switch that will not close until specific requirements have been met. Similar but not identical electrical interrupters are used in nuclear weapons.

F. Practicable Weapon Types

13F1. Bombs

Probably because the two fission weapons used in World War II were bombs, the popular press tends to group all nuclear ammunition under that classification. Frequently the only distinction it makes is between the A-bomb and the H-bomb. Though not strictly accurate, this popular manner of writing reflects the fact that nuclear weapons have been (and still are) adaptable to the delivery techniques used with conventional bombs.

TYPES OF BURST. As the foregoing section on fuzing techniques has already implied, nuclear bombs may be arranged to burst in the air, at the surface of the ground or water, or below either of these surfaces.

The effects on military objectives vary, to some extent, with the type of burst. The next chapter will summarize and compare those effects.

13F2. Missile heads

Almost as soon as fission weapons had been proved practicable, the thought of a guided missile with a nuclear explosive charge began to interest the ordnance designers. Since that time, all the armed services have developed reliable missiles capable of delivering nuclear payloads.

A quick check of unclassified sources indicates the following missiles having a nuclear capability: The Navy's Regulus I and II, Talos, and Polaris; The Army's Matador, Honest John, Corporal, Sergeant, Nike-Hercules, Redstone, and Jupiter; and the Air Force's Snark, Thor, Bomarc, Atlas and Titan.

13F3. Other applications

PROJECTILE. The Army has designed at least one nuclear projectile that can be fired successfully from a long-range field gun.

UNDERWATER WEAPONS. A conventional torpedo has two interchangeable heads—an inert head for exercise runs and an explosive-loaded war head. A third head bearing a nuclear charge is entirely practicable.

Nuclear equivalents of conventional mines and depth charges are also feasible.

13F4. Practical limitations

Whenever nuclear explosives are substituted for conventional ones, several practical problems must be faced and solved. One problem is to avoid trapping the planting craft and personnel within the explosion area. Another is to make reasonably certain that the military advantage to be gained is great enough to justify the expenditure of nuclear ordnance.

G. Delivery Systems and Techniques

13G1. Aircraft

The usual advantages and disadvantages of conventional aircraft bombing missions apply to missions involving nuclear weapons. The airplane is swift and maneuverable; it can penetrate far into enemy territory. It is, on the other hand, susceptible to radar detection and to countermeasures.

The airplane that drops a nuclear bomb must assure safety for itself. High-altitude launching can, of course, use distance as a safety factor. Pinpoint accuracy, however, is hard to achieve from a great height.

To assure greater accuracy of aim, a nuclear weapon may be launched from a comparatively low altitude. An adaptation of the loft, toss, or over-the-shoulder technique may be used. Accurate maneuvering and high escape velocity now have to be utilized as the safety factors.

13G2. Gun

As previously mentioned, the gun that fires a nuclear projectile is a long-range artillery type. Either a proximity fuze or a timer, as ordered, is usable with this projectile.

13G3. Guided missiles

Any guided missile, whether or not it bears a nuclear payload, requires a dependable launching system manned by a skilled team. Chapter 11 of this volume deals with representative shipboard missile-launching systems. Like the waterborne systems, the various land-based missile systems differ among themselves.

In the Polaris missile system, a submerged submarine is, in effect, the launching platform for a heavy-duty airborne weapon. When used for this purpose, the submarine has advantages that may revolutionize a number of military concepts. Except at close ranges, the submarine is harder to detect than a bombing plane. Nuclear propulsion and improved design have given the submarine a ranging power and a degree of maneuverability that would have seemed fantastic as recently as World War II.

13G4. Underwater ordnance

Torpedo tubes and other launching devices for conventional underwater weapons can be adapted to take nuclear weapons of comparable weight and shape, for use against submerged targets.

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H. Safety and Security

13H1. Safety precautions

In a nuclear weapon, three main classes of components are subject to specific safety precautions. One class is the conventional high explosive or propelling charge that must be used to achieve the supercritical mass of fissionable material. A second class is the complement of mechanical and electrical devices that provide a safe period, an arming cycle, and an initiating impulse. The third and final class, of course, is the nuclear material.

CONVENTIONAL EXPLOSIVES. General safety precautions for conventional explosives are summarized in NavOrd Instruction 5100.1. These basic rules apply in equal measure to nuclear ordnance, and to any separately stowed non-nuclear components that contain explosives. These rules should be familiar to the reader from his previous studies.

ELECTRICAL AND MECHANICAL COMPONENTS. As section E of this chapter has implied, the safety delays, arming arrangements, and fuzes used in nuclear ordnance are not radically different from their counterparts in other bomb-type and gun-type ammunition. Certain refinements have been made, but the underlying principles have not been superseded. For these components, as for conventional explosives, the Navy's standard rules must be known and enforced.

Special Weapons Ordnance Publications (SWOP's) on specific nuclear weapons supplement the standard Navy safety precautions wherever necessary.

NUCLEAR COMPONENTS. All personnel assigned to work with fissionable or fusionable materials must receive special training in the handling, stowage, and accounting methods peculiar to these materials.

Fissionable substances are, of course, radioactive. Therefore, as chapter 12 has explained, they constitute a radiation hazard that must be recognized and guarded against.

13H2. Security

Whether assembled in weapons or stored separately, radioactive substances are very costly and potentially very hazardous. Also, the details regarding the design and operation of specific nuclear weapons are extremely important to national defense. A breach of security regarding these matters might have grave consequences.

It is essential, therefore, that only personnel of unquestionable integrity, judgment, and patriotism have access to classified information on nuclear weapons. Officers who work in any capacity with these weapons must be careful at all times—on and off duty alike—to observe the spirit as well as the letter of the security regulations.

I. Elements of Organization

13I1. Preliminary

The organization for nuclear weapons is too large a topic to receive more than brief mention in this chapter. The general informational manuals of the several interested agencies, including the Bureau of Ordnance, give additional background information.

13I2. Atomic Energy Commission

In 1946 the Atomic Energy Commission (AEC) was established by act of Congress for the control of nuclear source material and the products derived from it.

Until 1953 the AEC developed and produced all United States nuclear ordnance. The three services participated jointly in formulating nuclear ordnance requests for the Department of Defense. These requests were forwarded to the AEC by way of a liaison committee.

Since 1953 many of the original functions of the AEC have been distributed among the three armed services. Each service develops its specific weapons systems, but parts of all these systems remain the responsibility of the AEC. Such parts must be procured from the AEC as explained in the next article.

13I3. Armed Forces Special Weapons Project

A tri-service agency called the Armed Forces Special Weapons Project (AFSWP) acts as the Department of Defense planning,

programming, and procurement agency for all AEC-developed ordnance items. Navy requirements for such items must be approved by the Joint Chiefs of Staff. They are then submitted to the AEC by way of the Bureau of Ordnance and AFSWP.

AFSWP reports directly to the Secretary of Defense regarding the status of all United States nuclear ordnance, including those items produced by the services.

TRAINING. AFSWP furnishes training and technical services to the three military departments. At first ALL training in nuclear weapons was under AFSWP control. Although the services have now developed their own training programs, AFSWP continues to furnish supplementary training, both to individuals and to groups. In particular, it orients and indoctrinates key officers.

TECHNICAL SERVICES. AFSWP determines the safety standards and physical procedures involved in the handling and transportation of nuclear weapons. It prepares plans and budget estimates for the military phases of nuclear weapon tests. It continuously reviews and evaluates the results of these tests, as a guide to the development of improved weapons and more effective defense measures.

1314. Storage sites

Within the continental United States, three types of storage sites, discussed below in the order of their relative size and complexity, are set aside for nuclear weapons and their components. Outside the continental United States, both land-based and shipboard storage facilities have been developed.

NATIONAL STOCKPILE SITES. The largest and most completely equipped land-based storage site for nuclear weapons is called a national stockpile site (NSS). It has facilities for storage, inspection, monitoring, maintenance, and calibration of a rather large number of weapons.

The weapons stored at an NSS are in AEC custody. The site itself is controlled and operated by AFSWP.

OPERATIONAL STORAGE SITES. For the non-nuclear components of nuclear weapons, an operational storage site (OSS) performs all the services that an NSS performs for the complete weapons. It may have similar facilities for the nuclear components.

Weapons at an OSS are in AEC custody or, sometimes, in Department of Defense custody. The site is controlled by one of the armed services.

LIMITED STORAGE SITES. Handling, temporary storage, and partial monitoring of non-nuclear components (and SOMETIMES of nuclear components) may be performed at a limited storage site (LSS). Complete storage and monitoring facilities may, under some conditions, be available at an LSS.

Weapons at an LSS are in Department of Defense custody. The site is controlled by one of the armed services.

A limited storage site located OVERSEAS is designated an OLSS.

VESSELS AS SITES. Two classes of naval vessels—the NVA and the NVB—serve as floating storage sites for nuclear weapons under Department of Defense custody. The NVA is roughly similar to the NSS, and the NVB to the LSS, in equipment and functions, though not necessarily with respect to size or capacity.

1315. Personnel

The selection of officers and men for assignment to nuclear weapons duties is under cognizance of the Chief of Naval Personnel. As has been mentioned, the standards for selection are necessarily very high.

Service schools and AFSWP both offer basic technical training. Individuals who have completed the content courses are organized into teams and trained to function as unified groups. Ordinarily a team specializes in one of the following duties: assembly and storage, loading, or disposal.

Naval special weapons teams are under the administrative control of the Gunnery Officer. Aboard ship each team is in the department most closely related to its functions. On an aircraft carrier, for example, the storage and assembly teams are in the gunnery department, while the loading team is part of the air department.

CHAPTER 14

EFFECTS OF NUCLEAR WEAPONS

A. Introduction

14A1. Preliminary

Whenever a new weapon is proposed, two questions arise. First, what can this weapon do for us in combat? Second, if the enemy uses the weapon against us, what defensive action can we take? The answers to these questions are seldom simple, even when the weapon is a "conventional" type. For nuclear weapons, the answers are complicated by two major factors. 1. The explosion is a very large one; 2. the explosion is accompanied, and often followed as well, by ionizing radiation.

When these two facts first became public knowledge, a certain amount of hysteria was inevitable. Hysteria still characterizes much of the popular thinking about nuclear weapons. Unbiased information, honestly faced and analyzed is an antidote to hysteria. A great deal of information on the effects of nuclear weapons has now been made available in unclassified Government publications. The data for these publications have come from two main sources—the World War II detonations over Japan and the postwar testing program.

Out of the wealth of available information, this chapter endeavors to summarize the details that are most likely to be useful to a junior officer. Regardless of specialty, every officer has cause to be familiar with the effects of nuclear explosions.

14A2. Plan

The brief second section of this chapter will review—and, where necessary, amplify—the major comparisons and contracts between conventional and nuclear weapons. The body of the chapter will analyze the effects of several possible types of nuclear explosions. Concluding sections will analyze the types of damage that can be expected, and will mention defensive measures.

B. Comparisons

14B1. Conventional reaction

A conventional explosion is a chemical reaction. An initiating impulse—usually heat or shock—is applied to a substance whose molecules contain oxygen, carbon, and hydrogen in abundance. When initiated, explosive substances oxidize (burn) much more rapidly than ordinary combustible materials. HIGH explosives (the substances used as the burster charge in conventional bomb-type ammunition) are said to detonate rather than to burn in the usual sense. The detonation propagates itself as an intense shock wave, followed immediately by a release of energy in the form of intense heat.

During this almost instantaneous process, the original molecules break up and their atoms recombine to form more stable compounds. Most of the energy of heat is converted to energy of motion that bursts the container and sends a blast wave through the air, or a shock wave through the earth (or water). It is primarily this blast or shock wave that causes damage.

However, the amount and type of damage can be modified by a number of considerations. These include (but are not necessarily limited to) the type and amount of the explosive substance, the strength of the target, and the distance between the target and the point of detonation. Frequently the target is shattered; sometimes it is ignited immediately. More frequently, fire damage to the target occurs (if at all) as a secondary result of shock damage to fuel systems, stowed explosives, or power lines. If the target is a ship, it may sink because it has been damaged beyond its capacity for rapid repair; or it may remain waterborne but be unfit for combat.

A successful conventional detonation is likely to kill or injure at least a few personnel. Some fatalities or casualties occur immediately and are unavoidable. Still others occur as a result of secondary effects. Their causes may be falling or flying objects, short circuits, fire,

flooding, or other resulting manifestations of explosive violence. A taut ship or station endeavors to keep secondary casualties to a minimum. This can be accomplished with enlightened foresight, training, and discipline.

14B2. Nuclear reaction

A nuclear explosive reaction, like a conventional one, is characterized by intense heat and a heavy wave of blast or shock. The heat is many times higher than in a conventional explosion; the shock wave, in addition to being stronger, moves more slowly and covers a much greater area. If all or even part of a nuclear explosion takes place in the air, winds of a high velocity are generated.

Secondary effects—falling and flying objects, damaged pipelines and wiring systems, and fires—are more numerous and extreme than after a conventional explosion. Unavoidable casualties may be numerous. Unhappily, other casualties (some of which could be avoided by using elementary knowledge and taking simple precautions) are liable to be very numerous.

In these respects a nuclear explosion differs from a conventional one in degree more than in kind. In another respect—the certainty of concomitant nuclear radiation and the possibility or probability of secondary radioactive contamination—the nuclear explosion is in a class by itself. Because nuclear radiation cannot ordinarily be discerned by any of the five senses, and because the average person has a vague and partially erroneous idea of the phenomenon, this aspect of a nuclear explosion—even more than the heavy blast and shock damage—is a possible source for panic.

The next section will describe the several major classes of nuclear explosions, and will summarize the effects of each on a target area.

C. Nuclear Explosions

14C1. Distribution of energy

Figure 14C1 shows how energy is distributed in a representative nuclear explosion. About 85 percent of the total energy appears first as intense heat. Almost immediately a considerable part of this heat is converted to blast or shock; the remaining thermal energy moves radially outward as heat and visible light.

Some 5 percent of the total energy appears immediately as invisible but extremely powerful nuclear radiation—alpha particles, beta particles, gamma rays, and neutrons. The residual nuclear radiation occurs over a long time; it is produced by the decay of the numerous radioactive isotopes that are formed by fission reaction.

Thus far we have been thinking of nuclear explosions in very general terms. The next few articles will take up weapons for which the yield (power) and the conditions accompanying the detonation are specifically mentioned. The first of these will be a nuclear weapon detonated in the air.

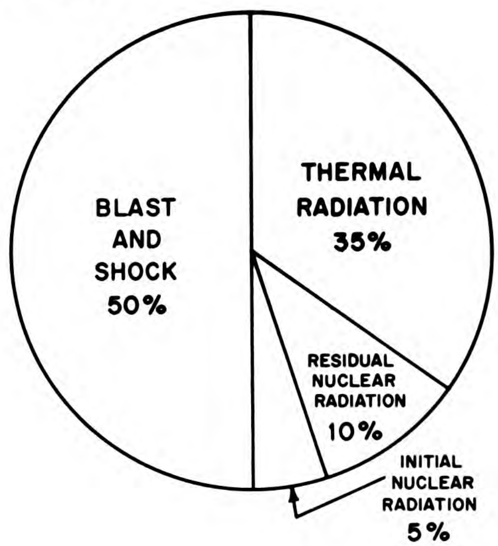


Figure 14C1.—A typical energy-distribution graph.

14C2. Representative air burst

As chapter 13 mentioned, an air burst over a target is frequently the most efficient means of accomplishing a military objective. A 1-megaton detonation (equivalent in destructive power to a million tons of TNT) has been selected for study in this article. For a weapon of lower yield, the distances and the time intervals would be shorter; for a more powerful weapon, they would be longer.

The three parts of figure 14C2 show what happens during the first 11 seconds after detonation.

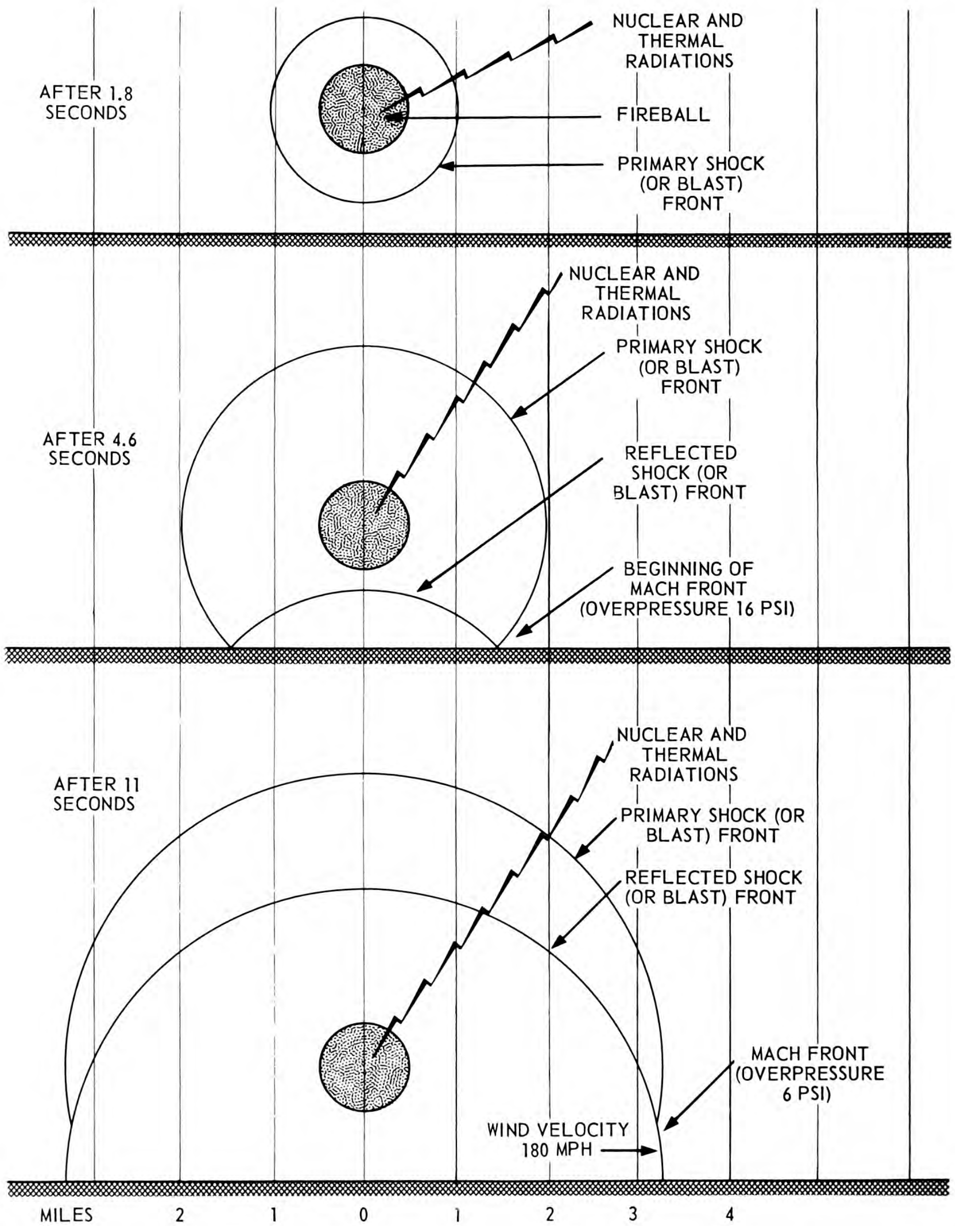


Figure 14C2.—Three stages in the development of a 1-megaton air burst.

Very soon after the nuclear weapon is triggered, a rapidly multiplying nuclear reaction vaporizes all parts of the weapon and its container. The reacting matter appears as an extremely hot and brilliant fireball resembling a small sun. The fireball radiates heat, light, and nuclear emissions.

The reaction causes a blast wave (the primary shock front) to move outward from the fireball. The air immediately behind this front acts as a terribly violent wind. In the first portion of figure 14C2 the blast wave has not yet reached GROUND ZERO (the point directly below the detonation point). The light rays and the equally swift gamma rays, however, have done so.

When the primary blast wave strikes ground zero with an impact like that of a tremendous hammer, a second or REFLECTED blast wave begins to move upward and outward from ground zero. The second part of figure 14C2 shows the reflected wave. At points on the surface, the impact of the two waves is felt simultaneously. This is true also, for practical purposes, of points ABOVE the surface in the vicinity of ground zero.

At points somewhat farther out, such as P^{i} and P^{ii} in figure 14C3, however, an object above the surface, such as the top of a tall smokestack or a television tower, would receive two distinct blows. It would be struck first by the incident wave moving radially outward from the fireball and, shortly thereafter, by the reflected wave moving radially outward from ground zero.

As one goes farther out from ground zero, however, the angular distance between the incident wave and the reflected wave decreases. In other words, the two waves are moving more nearly in the same direction. Also, the reflected wave tends to move faster, since the incident wave has compressed the air through which it will move. At some point between P^{ii} and P^{iii} in figure 14C3, the two waves begin to be felt as a single strong shock, not only at the surface (as before) but above it as well. This point marks the beginning of the MACH FRONT. For the explosion shown in figure 14C2, the overpressure (excess over normal atmospheric pressure) of the Mach front at its point of origin is 16 pounds per square inch.

As the combined waves move further from ground zero, the Mach front elongates itself, forming the Mach STEM shown extending almost vertically from points P^{iii} and P^{iv} in figure 14C3. An airplane or a tall object located ABOVE the triple point at the upper end of the Mach stem will feel two separate blast waves. An object BELOW the triple point will feel the combined blast waves as a single powerful

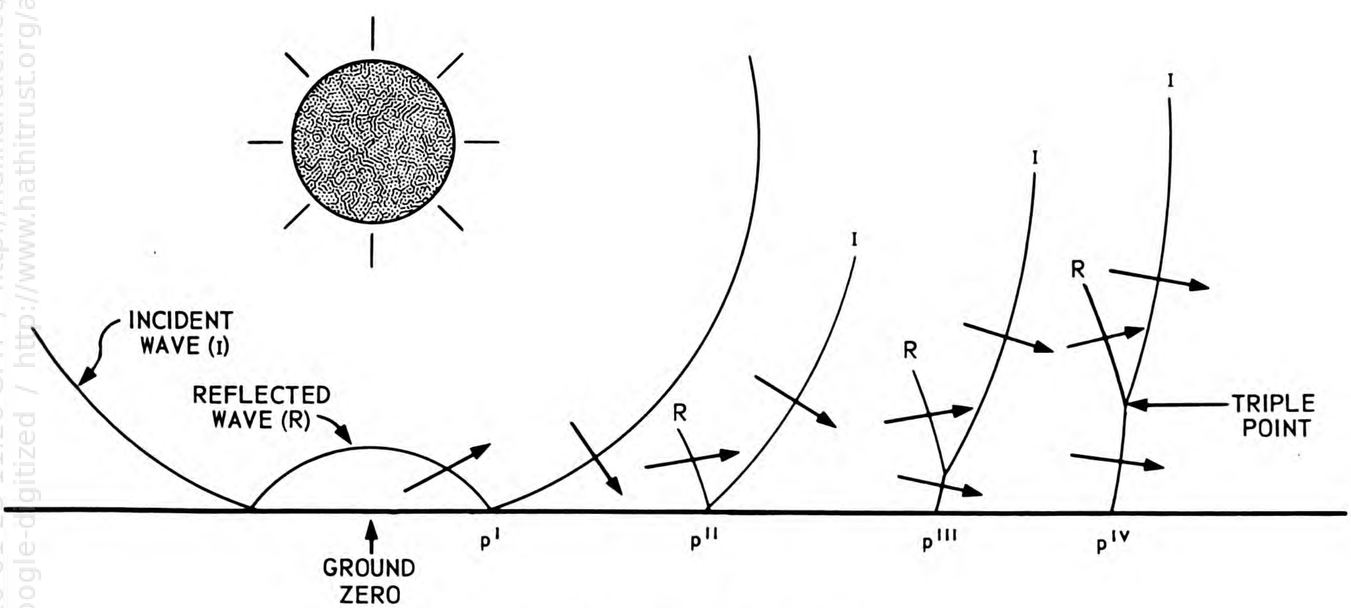


Figure 14C3.—Formation of the Mach front.

blow. The Mach effect is one reason for the long-range shattering power of a nuclear air burst.

Behind the primary shock wave and, after its formation, behind the Mach stem, a strong, swift wind blows almost horizontally outward from ground zero. In its destructive power, this wind is like a concentrated, short-lived hurricane.

While the Mach front is being formed, the fireball is still radiating large amounts of heat, light, and nuclear emissions. By the end of 11 seconds, for a 1-megaton explosion, the Mach stem has moved outward about 3 miles from ground zero. The overpressure is about 6 pounds per square inch, and the wind is blowing at 180 miles per hour. This is the situation shown in the third part of figure 14C2.

By the end of 37 seconds, however, significant changes have taken place, as shown in figure 14C4. The overpressure has dropped to a single pound per square inch, and the velocity of the wind behind the Mach stem is merely 40 miles per hour. The fireball has ceased to radiate much heat, but it is still emitting gamma rays given off by the decay of various short-lived radioactive isotopes formed during the fission reaction. This is an example of SECONDARY radiation, as distinguished from the primary radiation given off as an immediate result of the explosion.

Though it no longer glows, the fireball is still very hot. It rises swiftly, like a hot-gas balloon, sucking air inward and upward after it. This suction phase of the burst creates strong winds, opposite in direction to the Mach wind. Near ground zero these AFTERWINDS pull upward a large amount of surface dirt, plus much of the lighter debris from buildings shattered by the blast. This windborne material forms the stem of the mushroom cloud that is characteristic of a nuclear air burst. In figure 14C4 the cloud has begun to form.

Within the second minute after a 1-megaton detonation, the top of the mushroom cloud is about 7 miles in the air. The afterwinds are blowing inward toward ground zero at about 200 miles per hour.

The mushroom cloud consists mainly of vaporized fission products and other bomb residues, plus some of the lighter material carried up through the stem.

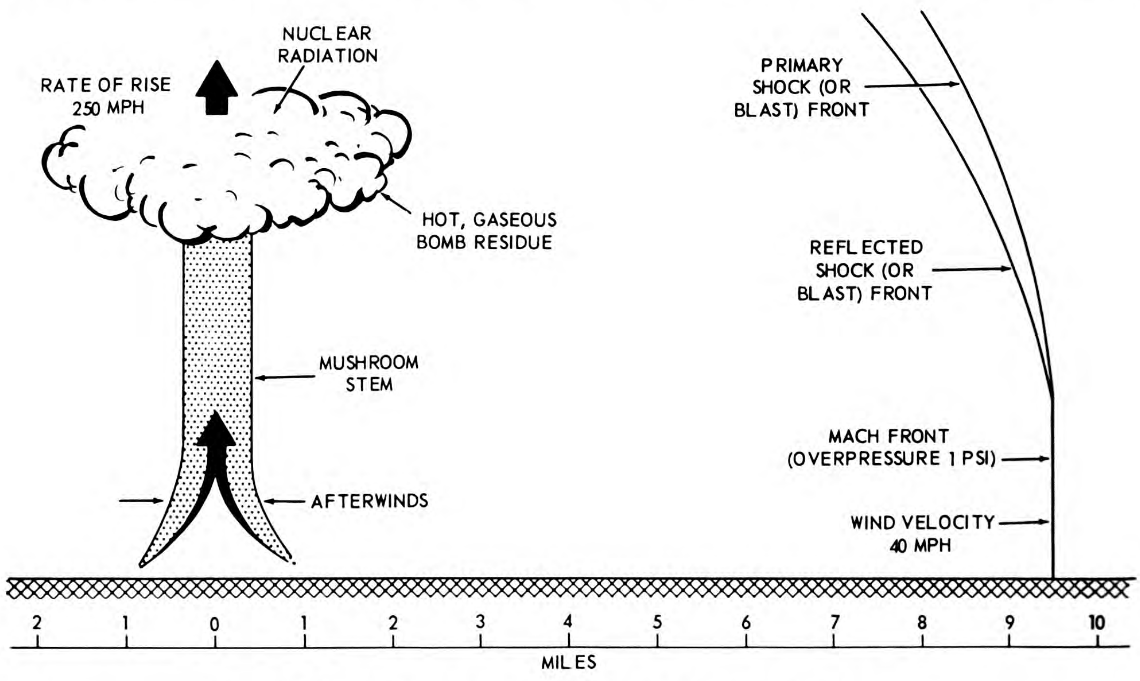


Figure 14C4.—Formation of the mushroom cloud after a 1-megaton air burst.

The fission products, of course, are highly radioactive.

After 10 minutes the mushroom cloud is about 15 miles in the air and has spread out considerably. In time, normal winds disperse the cloud, thus spreading its contents over a wide area and diluting them.

Because some of the radioactive fission products have very short half lives, the total radiation hazard is constantly decreasing by decay as well as by dispersal. It does not completely vanish, however. Fission products with long half lives, and diminishing quantities of those with short half lives, remain. Some of these may, in time, be borne earthward on raindrops, fog droplets, or dust particles; or they may descend by their own weight. This returning radioactive material constitutes the FALLOUT that is a peculiar hazard of nuclear explosions. (It may be mentioned in passing that the fallout from a high air burst is unlikely to be one of its serious threats. Fallout from some of the other types of bursts, however, is a major hazard).

The student should clearly understand that a non-fissioned water droplet or dust particle does not itself become radioactive by acting as a vehicle for a radioactive isotope. All it does is to convey this product of the original explosion from the upper atmosphere to some place where it may possibly be picked up by a living organism.

In considering a bomb of greater or lesser yield than a megaton, the order and nature of the events in an air burst will be as outlined in this article, but the statistical values will be different.

An air burst, then, produces intense heat radiation, primary nuclear radiation from the fireball, secondary nuclear radiation from the fission products in the mushroom cloud, great changes in atmospheric pressure, and strong, high-velocity winds, first away from ground zero and later toward it. At and near ground zero, any or all of the primary effects are fatal to personnel. The combination of pressure and wind destroys all light buildings, and possibly all buildings whatsoever.

Beyond the area of total immediate destruction, blast and wind damage are still heavy. Fires—resulting either from the initial heat radiation or from various secondary causes—soon reach dangerous proportions. Unprotected personnel may be killed or injured by radiation, by falling buildings, by blows or lacerations from falling or windborne objects, or by secondary fires. Many in underground shelters, and many above ground who have learned and applied elementary defense procedures, can save themselves or, if injured, can be saved by well-drilled rescue teams. The human body is much more tolerant of short-term overpressure than even the strongest buildings are. It is the secondary effects of overpressure—crumbling walls and flying glass, for example—that cause most injuries.

Because it is particularly destructive of structures and equipment (and because of minimized radioactive after effects), an air burst above a target area is likely to be a preferred method of nuclear attack. Other classes of bursts are possible, however. It is therefore necessary to notice how each compares with an air burst.

14C3. Surface burst

If an air detonation takes place at a very low altitude, part of the fireball, in its rapidly growing early stages, touches the surface of ground or water. This type of nuclear explosion is defined as a surface burst.

The intense heat of the fireball vaporizes a large amount of soil or water. This vaporized (but ordinarily not fissioned) extraneous material remains in the fireball as it rises. In addition, the suction phase of the explosion carries much more debris into the mushroom stem than would be expected in an air burst.

As the fireball cools, the vaporized foreign material condenses into minute particles in the mushroom cloud. The heavier debris falls back fairly near the point of burst; the lighter particles may remain airborne for a long time. Radioactive fission products may cling to any or all of the non-fissioned particles. The surface burst, therefore, carries a much greater threat of hazardous radioactive fallout than an air burst does. Though the danger from the fallout of heavy particles is greatest near the target (where damage from other causes is also severe) the airborne lighter particles may seriously contaminate wide areas.

It is estimated, for example, that a 1-megaton bomb, exploded on the surface of the ocean, would convert about 100,000 tons of water to vapor. At a high altitude, this water vapor would condense into droplets like those

in an ordinary cloud, with the serious difference that many droplets would be vehicles for radioactive fission products (plus an amount of induced radioactivity).[1] By the time these contaminated droplets fell as rain, they might be hundreds of miles from the point of detonation.

If any significant portion of the fireball touches land, a crater remains to mark the site of the explosion. The crater is formed partly by vaporization of the soil and partly by updraft into the stem during the suction phase. An observer at a distance can recognize a surface burst over land by the dirty color of the mushroom stem and cloud.

A varying portion of the kinetic energy of a surface burst goes into ground shock similar to that produced by a penetrating high-explosive bomb. This shock aids the atmospheric overpressure in demolishing buildings near the point of burst.

14C4. Underwater burst

A nuclear underwater burst is defined as one whose origin is beneath the surface of a body of water. Most of the energy of the underwater burst appears as underwater shock, but, a certain proportion (dependent on the depth) may escape and produce air blast.

A "true" underwater burst is one in which the detonation and the formation of the complete fireball both occur below the surface of the water. Because it is subject to hydrostatic pressure, the fireball is believed to be smaller than for a bomb of comparable yield detonated in the air. As the rising fireball touches the surface, its glow disappears, because the gases expand and cool when they meet the lesser resistance of the air.

While it is still under the surface, the fireball (or gas bubble) generates a shock wave, much as a fireball in the air generates a blast wave. A later paragraph will mention some of the peculiarities and military uses of this shock wave.

Two phenomena give advance warning that the fireball from an underwater detonation is approaching the surface. First a rapidly expanding white circle, called the SLICK, appears on the surface. The slick is composed of countless droplets of surface water that have been tossed up by the advancing shock wave. At the center of the slick, a dome of water and spray rises, directly over the detonation point.

Neither the slick nor the spray dome contains any radioactive matter. Neither of them has any interest except as a forerunner of the true explosion phenomena. (A very deep detonation may fail to produce a spray dome.)

When the radioactive fireball (or gas bubble) touches the surface, the hot gases are violently expelled into the atmosphere, drawing up with them a hollow column (sometimes described as a PLUME, or a CHIMNEY) of water. The complex pressure relationships cause water droplets to form a "Wilson" condensation cloud about the hollow column. The cloud formation reproduces, on a large scale, the conditions in the laboratory cloud chamber mentioned in chapter 12. The Wilson cloud remains only for a second or two, and is not radioactive.

Figure 14C5 shows three characteristic steps in a typical underwater burst. (Baker test at Bikini atoll in 1946—a 100-kiloton weapon was used in comparatively shallow water.) The upper part of the illustration shows conditions 2 seconds after detonation. Notice that the shock wave that surrounded the fireball in the water has become a blast wave in the air, surrounding the Wilson cloud.

Twelve seconds after detonation, as shown in the second part of figure 14C5, the water column has reached a height of about 3,300 feet. The fission products venting through the center of the column have begun to condense into an atomic cloud resembling a giant cauliflower.

The cauliflower cloud is strongly radioactive, but is too high to be a serious threat to shipborne personnel at this time. A much greater immediate threat is the BASE SURGE that has begun to form around the lower end of the hollow column. The base surge consists of radioactive mist from the contaminated water in the hollow column, which is now dropping

[1] Another source of radioactivity is the activity induced by neutrons when they are captured in the various elements present in the earth, sea, or other substance in the explosion environment. It may be mentioned in passing, that radioactivity induced by gamma rays from a nuclear explosion is either insignificant or completely absent.

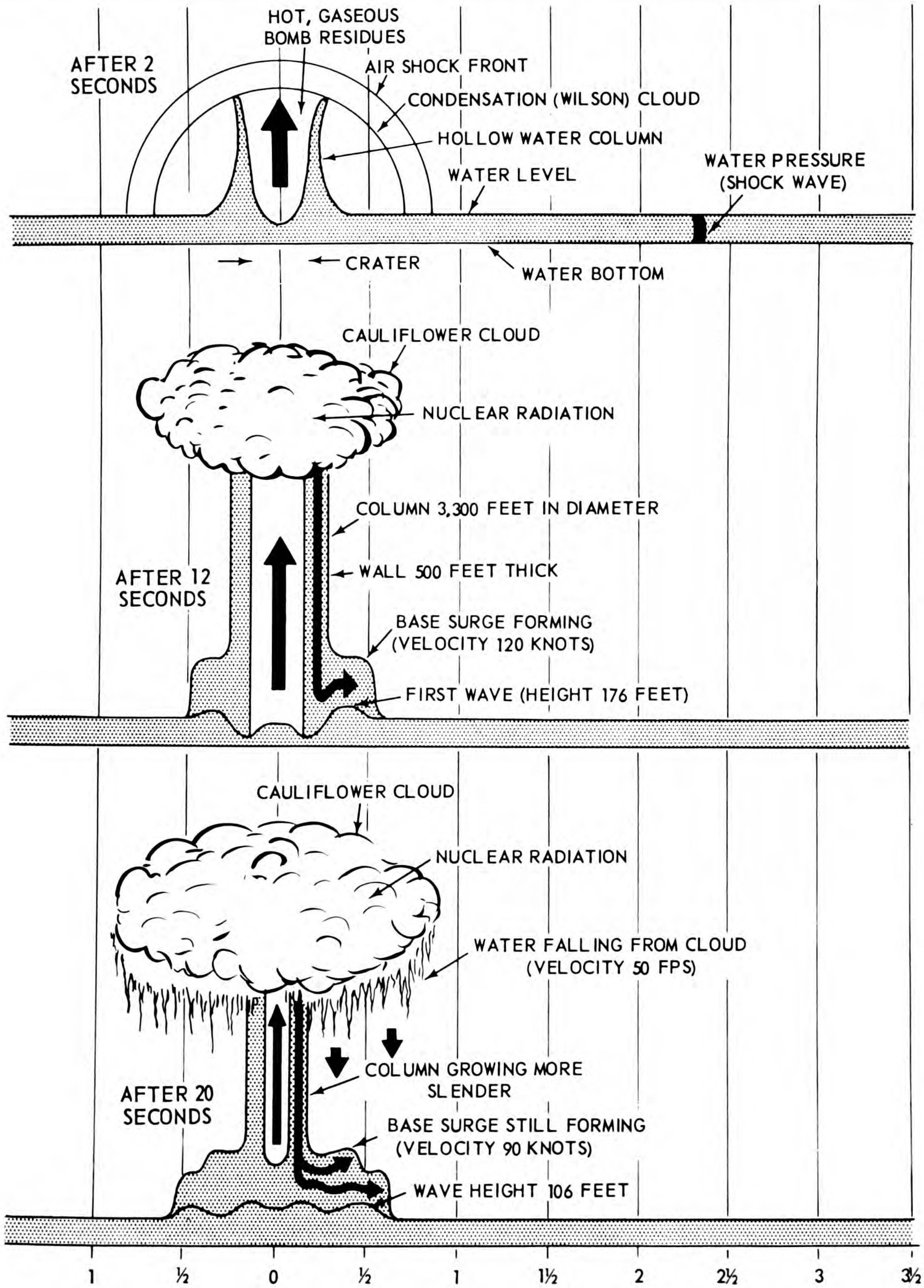


Figure 14C5.—Three stages in the development of a 100-kiloton shallow underwater burst.

backward due to gravity. The base surge spreads radially outward, giving the appearance of a doughnut-shaped cloud on the surface of the water.

By this time, too, large water waves have begun to form and move outward from the base of the hollow column.

By the twentieth second after detonation, conditions are as shown in the third part of figure 14C5. The base surge is growing higher as it moves outward. Large quantities of contaminated water, the MASSIVE WATER FALL-OUT, begin to pour down from the mushroom cloud. The hollow column is continuously shrinking.

A minute after detonation, the hollow column is much lower and the ring of outward-rushing base surge much higher. Contaminated water and spray from the cauliflower cloud encircle the hollow column. Water waves continue to form and move outward. The first wave has traveled almost a mile from the column.

Two and a half minutes after detonation, as shown in figure 14C6, the central column has been completely replaced by a radioactive mist or cloud that extends downward to the surface of the water. The base surge still forming an outward-moving ring around the central cloud, has lifted slightly. It appears, therefore, as a low-hanging cloud from which radioactively contaminated rain is pouring. This rain is hazardous to surface vessels in its path. The reader is to assume that the two portions of the base surge shown in figure 14C6 are cross sections of the ring-shaped cloud.

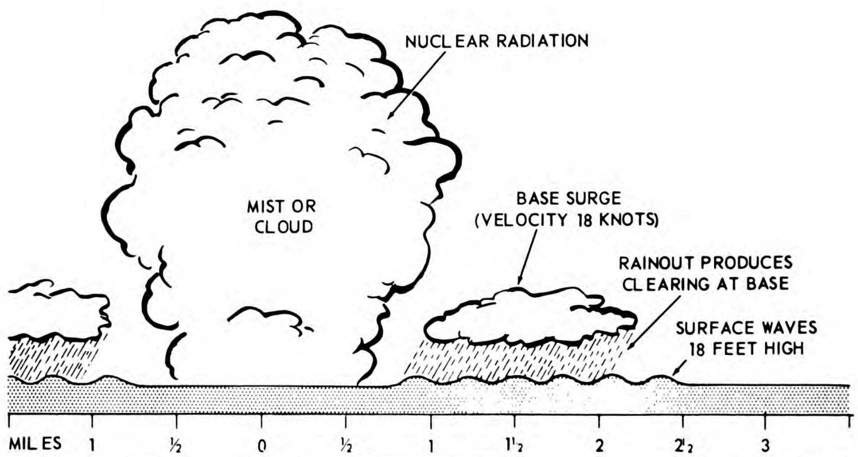


Figure 14C6.—Conditions 2-1/2 minutes after a 100-kiloton shallow underwater detonation.

Though diffusion, and the natural decay of isotopes with short half lives, have reduced the intensity of the nuclear radiation given forth by the central cloud, the level of radiation is still dangerously high.

Eventually, the central cloud and the base surge mingle and are carried off in the downwind direction.

An underwater detonation at greater depth may fail to produce any of the phenomena shown in figures 14C5 and 14C6. Instead, the hot gas bubble may break into a large number of smaller bubbles as it rises through the water. When the small bubbles reach the surface, they may break into radioactive froth, perhaps with a thin layer of contaminated mist above it. The mist is not likely to create a large fallout problem, but dangerous amounts of the radioactive foam may be washed against surface vessels or even against the shore.

During any type of underwater nuclear explosion, all or a great percentage of the radiant heat is absorbed by the water. Many of the first neutrons and gamma rays are also absorbed. When and if the fireball reaches the surface and bursts, however, the various fission products are still emitting gamma rays and beta particles.

The hollow column, the cauliflower cloud, and the base surge all contain large numbers of radioactive particles. The fallout (or rain-out) of these particles is liable to be the most serious danger to surface ships and shore installations BEYOND the region of heavy shock (and blast). It is important, therefore, that naval officers in general should have knowledge of decontamination procedures (as well as other damage control and first aid procedures).

14C5. Underground burst

When the fireball is formed below the surface of the soil, the hot, pressurized gas within it is mingled with bomb residues and vaporized earth. Upon breaking through the surface, the expanding gases throw up a hollow, outward-flaring column consisting of earth debris mingled with fission products.

As in an underwater burst, a hemispherical blast front surrounds the hollow column in its early stages. The upper part of figure 14C7 shows conditions two seconds after a 100-kiloton shallow underground burst. In addition to the phenomena shown in the drawing, this type of detonation produces a ground shock resembling a small earthquake, except that it occurs nearer the surface.

In rising the hollow column produces a THROWOUT of contaminated debris. The lighter products of the explosion form a radioactive cloud about the upper part of the column.

The CRATER is deeper and wider[2] than the one produced by a surface burst of equivalent yield.

By the end of 9 seconds, as shown in the second part of figure 14C7, the expanding cloud is still giving off hazardous amounts of radiation. Some of the heavier fragments in the throwout are falling back to the earth.

Forty-five seconds after detonation, the throwout is rapidly falling to the ground. It can be expected that finer dust particles from the hollow column will form a ring of base surge, much like the mist surge that characterizes a shallow underwater burst. The dust particles in the base surge are heavily contaminated with nuclear byproducts.

After a few minutes, as shown in the final part of figure 14C7, the central column loses its separate identity. The lightest particles from the column have now become part of the radioactive cloud. This cloud spreads out, especially in the downwind direction. If a base surge has formed, it rises toward the cloud and moves ahead of it in the downward direction. Thus, radioactive particles can be carried downwind for considerable distances, seriously contaminating a large area.

It is estimated that a 1-megaton shallow underground burst would blow into the air some ten million tons of soil and rock. The area around the crater would be heavily contaminated, and the fallout of lighter particles might be hazardous over a great distance.

D. Effects of Nuclear Explosions

14D1. Damage criteria

BASIC GRAPH. In assessing the damage caused by any explosion—whether "conventional" or nuclear—it is convenient to represent the various intensities of damage, and the areas subjected to each intensity, as a series of concentric circles about the detonation point. See figure 14D1.

Of course figure 14D1 is a simplified and generalized graph. To show the data gathered from the study of any particular explosion, this graph will have to be modified in one or several ways. For a nuclear explosion the several kinds of damage, and their separate or combined effects on equipment and personnel, are so varied that a series of graphs often becomes necessary to tell the story.

It may be desirable, also, to show a larger number of damage intensities than the four indicated in figure 14D1.

In actual practice there are no lines of demarcation between one damage area and another. Furthermore, the damage areas will seldom be perfect circles; sometimes they will vary greatly from the circular form.

[2] Comparison of CRATERING in dry soil for 100 KT weapon: contact surface burst-dia. 580' X depth 80'; underground burst at 50'-dia. 720' X depth 120'.

Nevertheless, for preliminary considerations, figure 14D1 is a useful tool.

DAMAGE AREAS. In any effective explosion of bomb-type ammunition, there is a large or small area about the point of burst where total destruction of equipment and personnel must be taken for granted. In a nuclear explosion at or below the surface, nothing within or near the fireball will be salvageable. With an air burst (except a very high one), ground zero and a greater or lesser area surrounding it can be considered completely demolished. For a nuclear weapon of any type, the area of TOTAL destruction is many times larger than for a conventional weapon of comparable size.

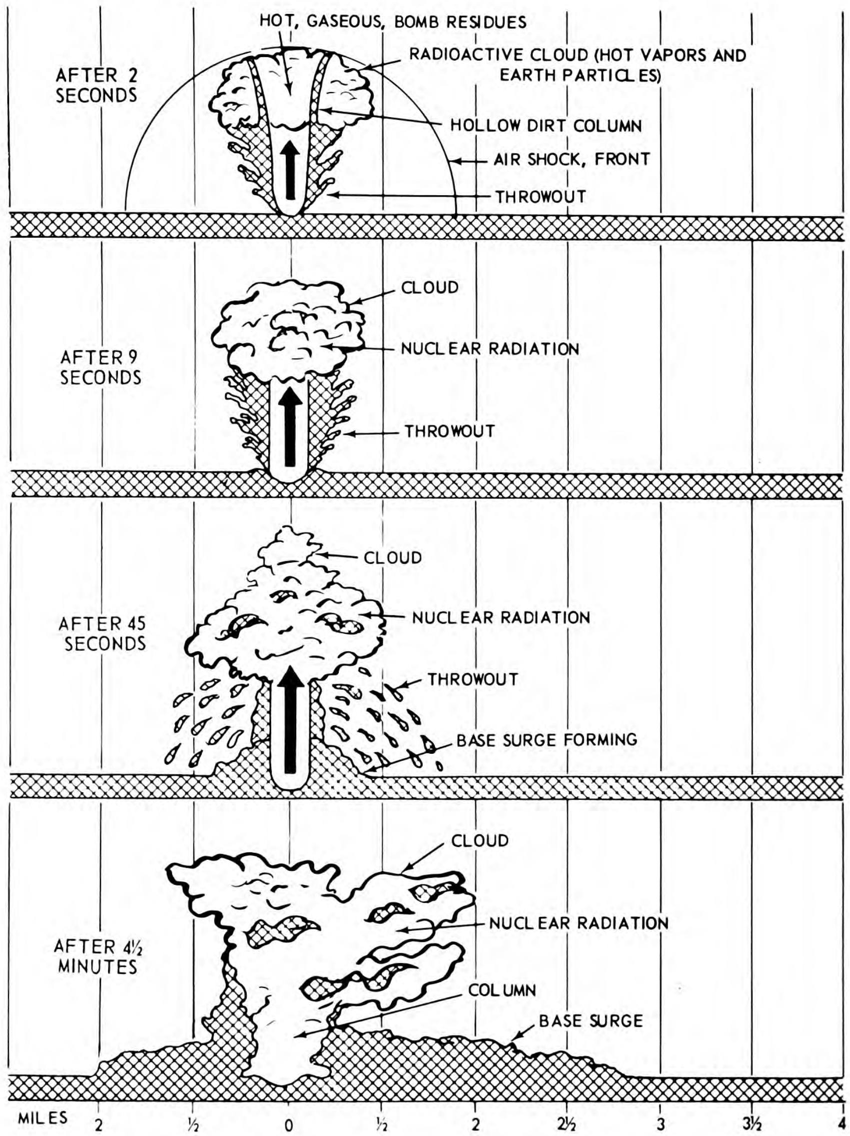


Figure 14C7.—Development of a 100-kiloton shallow underground burst.

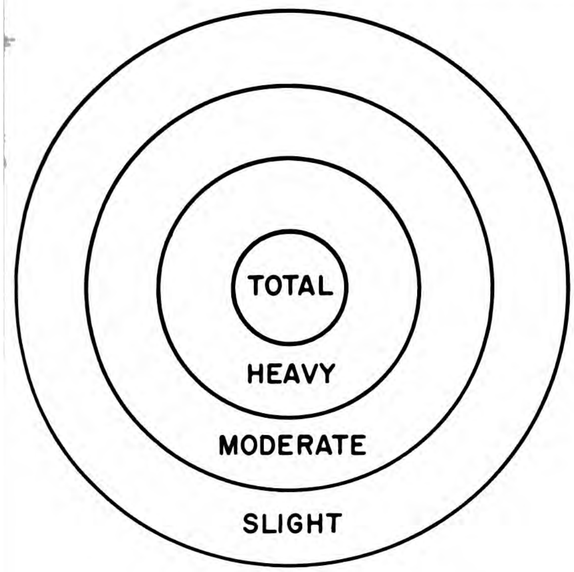


Figure 14D1.—A basic damage graph.

Ashore, in the HEAVY damage area, many ıuildings, much equipment, and many persons vill be lost, either within a few seconds after letonation or as a result of secondary pheıomena. Some buildings and equipment, and ome people as well, may suffer only minor ırimary damage. The final number of casulties in the heavy damage area will depend, in ıart, on the speed, level-headedness, ingenuity, ınd cooperation displayed by disaster-relief ıersonnel.

This chapter will not go into details about 'atomic defense". As a junior officer you will 'eceive further indoctrination in fundamental ırocedures and will be assigned a definite reponsibility for some part of the total program ıf your ship or station.

In the zone of MODERATE damage, there vill, of course, be some heavy damage to light equipment and structures. There will also be ome fatalities and severe casualties to personnel. Some persons, however, will be unıarmed, and many will be able to do useful vork after receiving simple first aid. The great problems will be (1) to prevent panic and 2) to utilize all able-bodied (and mentally or emotionally competent) personnel in damage control and disaster relief. At a shore station, ire fighting (possibly with severely damaged equipment) will be vitally necessary.

Within the zone of SLIGHT damage, the nain problems will be to prevent panic, to ascertain that previously trained teams and groups are functioning properly, and to make such adaptations as are ordered by higher authority. One duty, even in this area, will be to watch for fires and get them under control.

The next few articles will explain the several kinds of damage that can be expected from nuclear explosions.

14D2. Air blast

This chapter has already mentioned that an air burst of a nuclear weapon above a target has tremendous destructive capability and, therefore, great military usefulness. For a short distance from the fireball, the blast damage from a surface burst may be even greater, but the effective range tends to be shorter. Blast damage can also stem from shallower subsurface bursts.

Blast damage from a nuclear explosion really has two distinct causes. One cause is the OVERPRESSURE that has already been defined and described. The other cause is the DRAG exerted by the nuclear windstorm.

OVERPRESSURE DAMAGE. A given point in space is subjected to peak overpressure when the primary blast wave (or, in the Mach region, the Mach wave) strikes it. This is the time when a structure or vehicle is most liable to collapse, as though from a hard blow. After the peak, the atmospheric pressure at the given point gradually drops back to normal. Shortly afterward, the pressure is reduced below normal by the suction phase of the explosion. The drop below normal is never as great as the previous rise above it; but it, too, can cause damage.

Massive, comparatively low buildings of reinforced concrete, and low masonry buildings strengthened by heavy steel skeletons, are the only structures likely to withstand 15 or more psi (pounds per square inch) of peak overpressure without severe damage. Light wood or masonry buildings—typical living accommodations—receive m o d e r a t e damage from 2 to 3 psi.

Naval vessels are constructed to withstand battle shock and constant pounding from the waves. Peak overpressures of 5 psi cause light damage to most types of surface ships, while overpressures required for severe damage vary from 25 psi for destroyers to 40 psi for heavy cruisers. A ship's boilers, uptakes,

and ventilation system are especially vulnerable to overpressure.

Some tanks and other heavy-duty shore equipment have withstood 20 to 30 psi.

Strangely enough, the human body has been known to stand short-term overpressures up to 100 psi without severe or permanent damage. Of course, resistance to overpressure, like other resistances, varies with the individual. Nevertheless it is safe to assume that personnel injuries and fatalities traceable to overpressure will be caused indirectly—usually by the collapse of heavy equipment and structures.

DRAG DAMAGE. Drag (sometimes called DYNAMIC PRESSURE) refers to the effects of the WINDS, as distinguished from the pressure changes that cause and immediately precede these winds.

Article 14C2 mentioned that an air burst is characterized by violent winds blowing radially outward from ground zero and, a short time later, by afterwinds blowing inward. The drag of these winds is particularly destructive to lightweight walls, and to tall objects such as antennas and flagpoles. Power lines, bridge spans, and parked vehicles are also vulnerable to drag.

Drag, rather than overpressure, is the blast phenomenon that seriously threatens the many personnel who might otherwise suffer only slight injuries. The winds of a nuclear explosion can impel heavy or sharp objects with tremendous force, thus converting everyday materials into deadly weapons. A man who has survived peak overpressure intact may leave cover too soon, only to be killed by a brickbat hurled against his temple, or a glass splinter driven into or through his body.

Table 14D1 and figure 14D2 give some indication of the relationships between overpressure, wind velocity and dyanmic pressure (drag force). Dynamic pressure is a function of the wind velocity and the density of air behind the shock front. Like the peak shock overpressure, the peak dynamic pressure decreases with increasing distance from the explosion center, although at a different rate as can be seen in the illustrations. (The dynamic pressure decreases more rapidly than does the shock overpressure.)

For the purpose of this orientation, let it be said that certain structures are more susceptible to damage by the drag forces inherent with air blast, while others are more sensitive to shock overpressure.

Table 14D1

Peak over-pressure (psi)	Peak dynamic pressure (psi)	Maximum wind velocity (mph)
72	80	1170
50	40	940
30	16	670
20	8	470
10	2	290
5	0.7	160
2	0.1	70

Figure 14D3 indicates the damage-distance relationships for a sampling of structures more sensitive to overpressure. Other damage-distance relationship data is available in the bibliography.

NUCLEAR-HIGH EXPLOSIVE COMPARISON. Although the blast effects of nuclear and conventional explosives were compared in the beginning of this chapter, an additional difference between the two should be pointed out here. The combination of very high peak overpressures, together with the much longer duration of the positive phase of the blast wave from nuclear explosions, results in "mass distortion" of buildings and structures—similar to that caused by earthquakes. An ordinary explosion will usually damage only part of a large building, but the nuclear blast can surround and destroy it entirely.

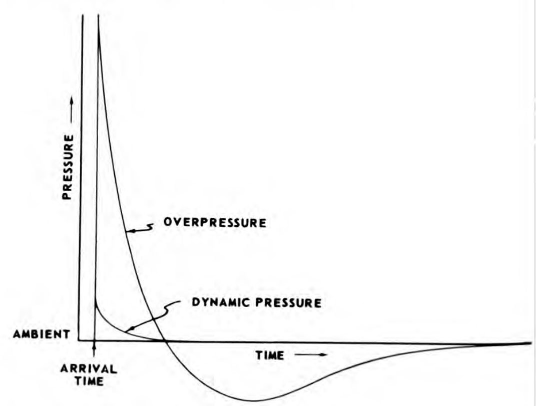


Figure 14D2.—Variation of overpressure and dynamic pressure with time at a fixed location.

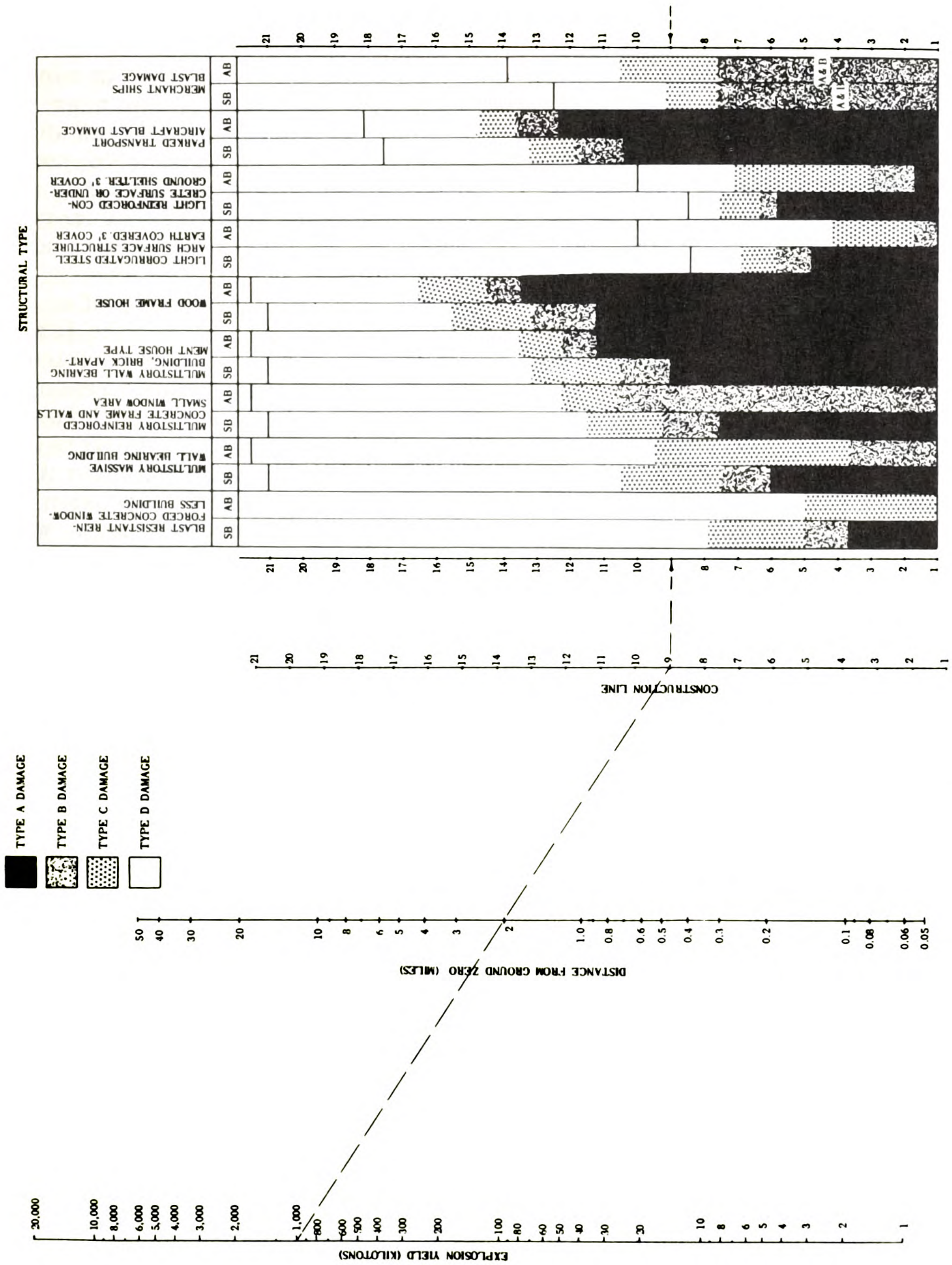


Figure 14D3.—Damage-distance relationships for structures (diffraction type).

14D3. Shock

When all or part of the fireball strikes or is formed below the surface, a shock front in the earth (or water) corresponds to the blast front in the air.

GROUND SHOCK. As has already been mentioned, ground shock resembles a small earthquake, except that it originates much nearer the surface.

Ground shock is a threat to land-based personnel, because it can demolish or damage underground shelters. In the bomb crater, of course, these would be totally destroyed. For a short distance beyond the actual crater, the zone of total destruction would continue. Beyond that would be a zone of heavy damage consisting of severe distortion and partial collapse.

The effects of underground shock tend to fall off rapidly, however, Too, when shock ceases to be severe, effects from it become almost negligible. In a subsurface burst, if any part of the fireball breaks through the surface, the blast damage above ground is likely to be more extensive than the shock damage below it.

Buried utility pipelines would be destroyed within the crater and would be damaged at distances up to three times the radius of the crater. Near the crater, the pipes themselves would rupture. Farther out, the joints, especially between horizontal pipes and risers, would tend to rupture.

Well constructed tunnels and subways, particularly in granite bedrock, are resistant to underground shock. Complete demolition would be likely to occur only within or near the bomb crater.

UNDERWATER SHOCK. A shock wave formed under the surface of the water behaves much like a similar wave in air. Since water is a denser fluid than air, the values of normal pressure and overpressure are correspondingly higher. The reduction after peak overpressure is more gradual than in air.

The shock wave in water may produce a reflected wave by striking the bottom or any rigid submerged object. If conditions are favorable, the primary wave and the reflected wave may fuse to produce a phenomenon comparable to the Mach front in air.

When the shock wave touches the upper (or air) surface of the water, a peculiar phenomenon occurs. Because air is lighter and less resistant than water, the wave reflected back from the contact point is a RAREFACTION (or suction) wave. When the rarefaction wave reaches any given point below the surface, a sharp pressure reduction, called CUTOFF, occurs.

From the military point of view, cutoff is important because at points near the surface it follows so closely after peak overpressure that one phenomenon tends to neutralize the other, thus reducing the damaging power of the explosion. For shallowly submerged targets, therefore, nuclear weapons may not always be fully effective.

The primary shock wave of an underwater nuclear explosion strikes the target ship or other object with a sudden violent blow. In this action a nuclear weapon resembles a conventional one—with one significant difference. The conventional weapon delivers its blow at a single point or over a comparatively small area; while the nuclear explosion acts simultaneously over a large area with all encompassing force.

Underwater shock damages a vessel in one (or both) of two ways. First, it may rupture or at least weaken the hull. Second, it may distort, rupture, or break loose any of the various ship's components or installations. Piping, shafting, air vents, and boiler brickwork are susceptible to damage. Platforms supporting heavy equipment may be weakened or thrown out of proper alignment. Light objects may be thrown about so violently that they become a serious threat to personnel (missile hazards).

In the effects just mentioned, an underwater nuclear burst is similar to a conventional mine or depth charge. The major difference lies in the extended damage radius of the nuclear weapon.

14D4. Thermal radiation

Within a few milliseconds after the detonation of a nuclear weapon, intensely hot gases at tremendously high pressures, rapidly form a highly luminous mass known as the "fireball" or "ball of fire." At about seven-tenths of a millisecond, the fireball from a 1-megaton nuclear weapon would appear to be more than 30 times as bright as the sun at noon to an observer 60 miles away. Although the size of

:he fireball will vary with the bomb energy, :he luminosity does not vary greatly. However, the larger the yield of the weapon, the onger will be the PERIOD of luminosity. Within this seven-tenths of a millisecond from ime of detonation, the fireball of a 1-megaton weapon will have reached a diameter of 440 eet. The fireball increases to maximum diameter of about 7200 feet[3] at plus 10 seconds. t is then rising at the rate of approximately 00 mph. After a minute, the ball of fire has ooled to an extent that it is no longer visible.

The nuclear explosion has often been comared to the conventional high explosive detoiation in that, except for the yield and nuclear adiation involved, they can be considered imilar. When referring to thermal effects, his can be a poor comparison because of the ery large proportion of energy released as hermal radiation by a typical nuclear exploion. As was illustrated in figure 14C1, over ne-third of the energy of a typical nuclear xplosion manifests itself in the form of hermal radiation. Too, the temperatures inolved in a nuclear explosion are much higher han with conventional explosives.

Thermal radiation travels with the speed of ight, so that the time elapsing between its mission from the ball of fire and its arrival at target a few miles away, is quite insignificant.

Much like the sun, the fireball radiates ltraviolet (short wave length) as well as visile and infrared (long wave length) rays. Due certain phenomena associated with the aborption of thermal radiation by the air in ront of the expanding fireball, the SURFACE emperature undergoes a curious change. While the interior temperature of the fireball alls steadily, the surface temperature dereases more rapidly for a small fraction of second, then it increases again for a somehat longer time, after which it falls continuusly. In other words, there are effectively WO SURFACE-TEMPERATURE PULSES— he first of very short duration, the second asting for a relatively long period of time see fig. 14D4). These surface-temperature ulses correspond to the pulses of thermal nergy radiated from the fireball. In a 1-megaton nuclear explosion, the first pulse lasts for about a tenth of a second. The temperatures are very high, and much of the radiation is in the ultraviolet region. Moderately large doses of ultraviolet radiation can produce painful blisters. Even small doses can cause reddening of the skin. However, in most circumstances, the first pulse of thermal radiation is not a significant hazard. The situation with regard to the second pulse is quite different. This pulse may last for several seconds, and it carries about 99% of the total thermal radiation energy of the nuclear explosion.

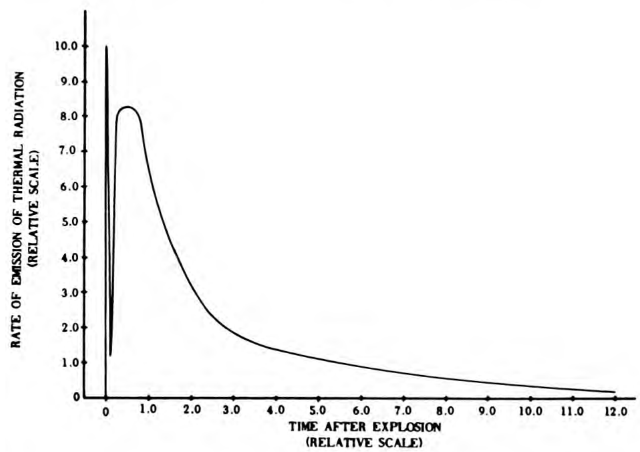


Figure 14D4.–Emission of thermal radiation in two pulses.

The large amount of thermal radiation characteristic of the nuclear explosion has important consequences. For although most of the destruction from a nuclear air burst is the result of blast—thermal radiation will make a significant contribution to the overall damage through the ignition of combustible materials. Additionally, thermal radiation is capable of causing skin burns on exposed personnel at distances where the effects of blast and initial nuclear radiation are insignificant. This difference between the injury ranges of thermal radiation and the other effects mentioned becomes more marked with increasing nuclear weapon yield.

The most important physical effects of the high temperatures resulting from the

Through the use of a scaling law, together with the results of various nuclear test explosions, it s possible to compute the fireball radius "R" for a nuclear weapon of "W" kilotons equivalent. R (in feet) = 230 W to the 2/5 power.

absorption of thermal radiation are: burning of the skin and scorching, charring, and possible ignition of combustible organic substances such as wood, fabrics, and paper.

Thin or porous materials, such as lightweight fabrics, newspaper, dried grass, and dried rotted wood, may flame when exposed to sufficient thermal radiation.

Table 14D2 supplies a comparison of approximate thermal energies required to produce a variety of physical effects.

Table 14D2[4]

Effects	Approx. cal/cm² required:		
	1 KT	100 KT	10 MT
Second-degree bare skin burn	4	5	9
Newspaper ignition	3	5	9
White pine charring	10	18	32
Army khaki summer uniform destruction	18	31	56
Navy white uniform destruction	34	60	109

[4]Thermal energies are expressed in calories per unit area--square centimeter. Note that the amount of energy required for burning, charring, etc., varies inversely with the yield of the nuclear weapon. This is because of the rate at which the energy is delivered. For a given total amount of thermal energy received by each unit area of exposed material, the damage will be greater if the energy is delivered rapidly than if it is delivered slowly. This means that in order to produce the same thermal effect in a given material, the total amount of thermal energy (per unit area) received must be larger for a nuclear explosion of high yield than for one of lower yield, because the energy is delivered over a longer period of time, i.e. more slowly, in the former case.

Figure 14D5 indicates how thermal energy varies with distance for a selected yield nuclear weapon. The graph assumes a reasonably clear state of atmosphere.

Thick organic materials, such as plastics, heavy fabrics, and wood more than 1/2 inch thick, char but do not burn. Dense smoke, even jets of flame may be emitted, but the material does not sustain ignition. This type of behavior is illustrated in the photographs taken of a white-painted wood frame house during one of

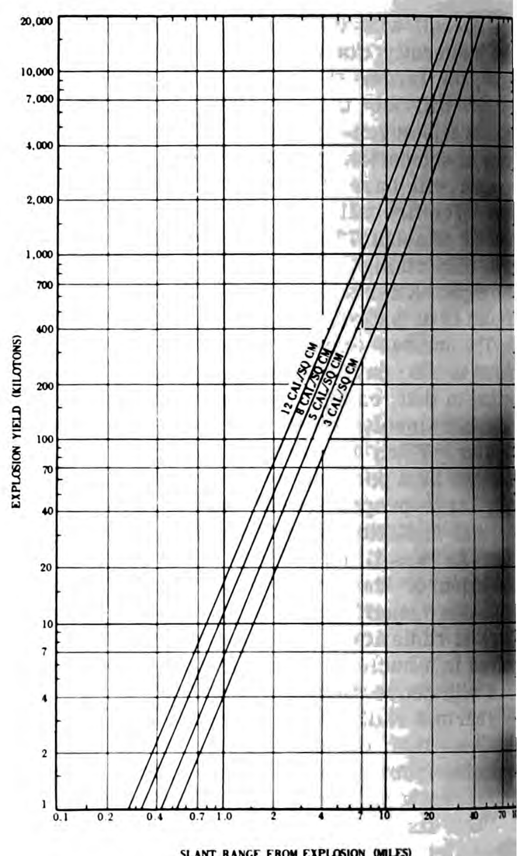
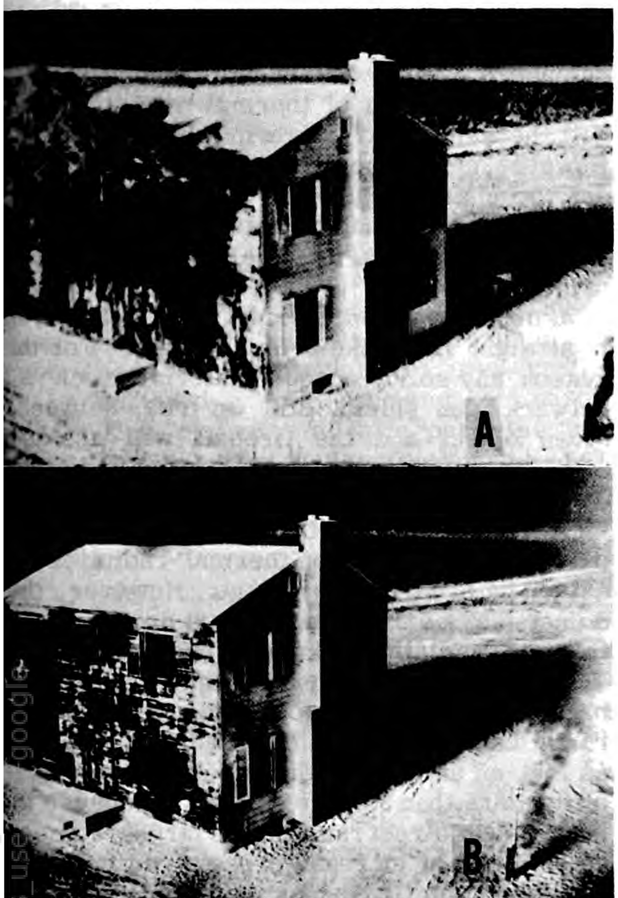


Figure 14D5.—Thermal energy received at various slant ranges.

the nuclear tests in Nevada. Thus, figur 14D6a indicates that at virtually the instant o the explosion, the house became covered wit thick black smoke, and no sign of flame. Ver shortly thereafter, but before the arrival of th blast wave, the smoke ceased as indicated i figure 14D6b. Thin combustible material woul probably burst into flame at the same locatior

But perhaps the most serious consequenc of thermal radiation is its ability to produc serious burn injury to personnel at lon ranges. Figure 14D7 is included to show th ranges for moderate first-, second-, and third degree burns from nuclear explosions. Th graph is computed assuming a typical air burs with clear atmospheric conditions prevailin For a typical surface burst, the distance would need to be scaled down to about 60% those stated.



'igure 14D6.—a. Thermal effects on wood frame house lmost immediately after explosion (about 25 cal/sq cm); . thermal effects on wood frame house 2 seconds later.

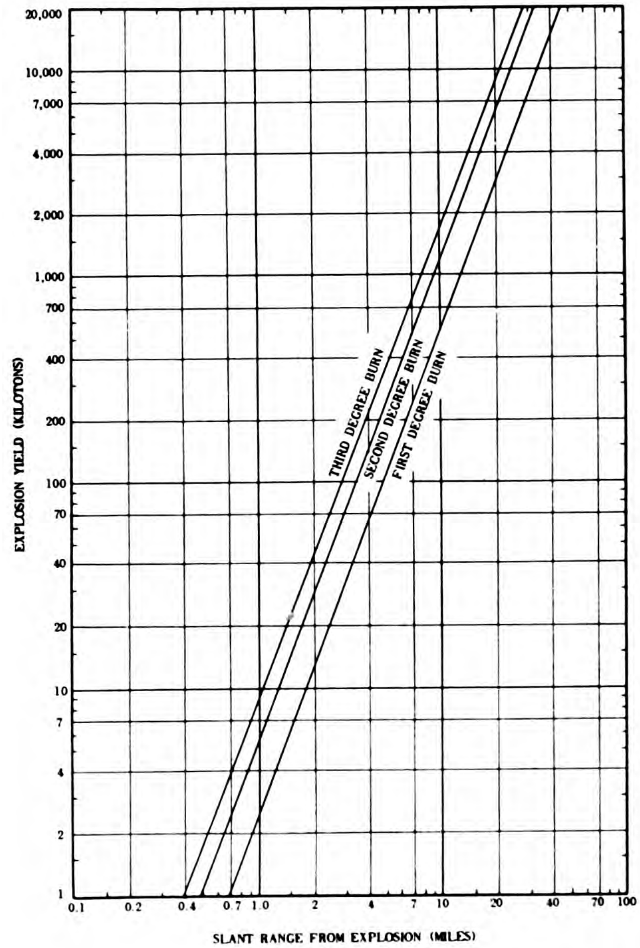


Figure 14D7.—Distances at which burns occur on bare skin.

Reading the graph, it can be seen that peronnel exposed to a typical air burst (1 MT exlosion) at 9 miles might be expected to reeive moderate second-degree burns.

Conventionally, burns are classified acording to their severity, in terms of degree or depth) of injury. In first-degree burns ıere is only redness of the skin. A moderate unburn is an example of a first-degree burn. lealing should occur without special treatment nd there will be no scar formation.

Second degree burns are deeper, more seere, and are characterized by the formation f blisters. A severe sunburn is an example of second-degree burn.

In third-degree burns, the full thickness of ıe skin is destroyed. Unless skin grafting chniques are employed, there will be scar ırmation at the site of the injury.

The extent of the area of skin which has been burned is also important. Thus, a first degree burn over the entire body may be more severe than a third degree burn to one spot. The larger the area burned, the more likely is the appearance of symptoms involving the whole body. Further, there are certain critical, local regions, such as the hands, where almost any degree of burn will incapacitate the individual.

Thermal radiation can be the cause of flash burns or flame burns. Flash burns are directly caused by the radiant energy of the fireball. Flame burns are distinguished from flash burns in that they are caused by fire, no matter what the origin. Flame burns occur as a secondary result of thermal radiation, for example, those resulting from the fires started by thermal radiation.

A highly significant effect of the nuclear explosion is the very large number of flash burns. This was one of the most striking facts about the nuclear bombing of Japan in World War II. It has been estimated that 20 to 30 percent of the fatal casualties at Hiroshima and Nagasaki were due to flash burns, as distinct from flame burns. Though significant, it should be realized that these illustrated results were magnified due to the fact that the atmosphere was very clear and that the summer clothing worn was light and scanty.

Another danger of a nuclear explosion is its possible effect on the eyes. Thermal radiation can cause both retinal burns and flash blindness.

Because of the focusing action of the lens of the eye, enough energy can be collected to produce a burn on the retina at such distance from a nuclear explosion that the thermal radiation intensity is too small to produce a skin burn. As a result of accidental exposures during nuclear tests, a few retinal burns have been experienced at a distance of 10 miles from the explosion of a 20-KT weapon. It is believed that under suitable conditions, such burns might have resulted at even greater distance. Retinal burns occur so soon after the explosion that reflex actions, such as blinking and contraction of the eye pupil, give only limited protection. In all instances, there will be at least a temporary loss of visual acuity, but the ultimate effect will depend on the severity of the burn and on its location on the retina.

Because of the more or less remote chance that an individual will be looking directly at the ball of fire, the chance of temporary "flash blindness" or "dazzle," due to the flooding of eye with brilliant light is much more prevalent than retinal burns. Flash blindness is of a temporary nature and vision is regained within a comparatively short time. However, flash blindness is of military significance, since it may extend to 2 or 3 hours.

When thermal radiation falls upon any material or object, part may be reflected, part will be absorbed, and the remainder, if any, will pass through and ultimately fall upon other material. It is the amount of radiation ABSORBED by a particular material that produces heat and so determines the damage suffered by that material. Highly reflecting and transparent substances do not absorb much of the thermal radiation and so are relatively resistant to its effects. A thin material will often transmit a large proportion of the radiation falling upon it, and thus escape serious damage. A dark fabric will absorb a much larger proportion of thermal radiation than will the same kind of fabric when it is white. However, a light-colored material which blackens (or chars) readily in the early stages of exposure to thermal radiation will behave essentially as a dark material regardless of its original color.

Unless scattered, thermal radiation travels in straight lines like ordinary light. For this reason any solid, opaque material, such as a bulwark, gun shield, hill, or tree, between a given object and the fireball will act as a SHIELD and thus provide protection from direct thermal radiation.

ATMOSPHERIC CONDITIONS also play a part in the amount of thermal radiation received by a particular object. However, they do not play as important a part in attenuating thermal radiation as was once suspected. When visibility is in excess of 2 miles (light haze or clearer), the total amount of thermal radiation received will be essentially the same as that on an "exceptionally clear" day (visibility more than 30 miles). This is because any decrease in direct radiation is largely compensated for by an increase in scattered radiation.

When visibility is less than 2 miles because of rain, fog, or dense industrial smoke, there will be a definite decrease in radiant energy received at any specified distance.

CLOUDS can also affect the amount of radiant energy received. For example, if an explosion occurs above a cloud layer, there will be considerable attenuation at ground level. Conversely, should an explosion occur beneath a cloud layer, some of the radiation which would normally have been lost to space will be scattered back to earth.

Artificial white (chemical) SMOKE can be used to attenuate thermal radiation, for it acts like fog in this respect. A dense smoke screen between the point of burst and a given target can reduce thermal radiation to as little as one-tenth of the amount which would otherwise have been received at the target.

14D5. Nuclear radiation

It has been previously pointed out that 15% of the total energy yield of a typical nuclear

weapon is distributed in the form of nuclear radiations (fig. 14C1). Let us explore further what this radiation consists of, how it occurs, and what its dangers are.

In any nuclear explosion there is an initial flux of radiations consisting mainly of gamma rays and neutrons. Both of these (especially gamma radiation) travel great distances through the air, and can penetrate great thicknesses of material. Remaining within the fireball are fission products and unfissioned bomb[5] material. These fission products and unfissioned bomb material are also radioactive, and emit gamma rays and beta particles[6]. This emission of beta particles and gamma rays from the radioactive substance is a gradual process, and its hazard therefore remains over a significant period of time.

INITIAL NUCLEAR RADIATION is arbitrarily[7] defined as that radiation emitted within (approximately) the first minute after the explosion. Initial nuclear radiation includes those neutrons and gamma rays given off almost instantaneously, as well as the gamma rays given off by the radioactive fission products in the rising cloud[8].

It follows that RESIDUAL RADIATION is that emitted after approximately one minute from the instant of a nuclear explosion. This radiation originates mainly from the bomb residues; that is, from the fission products and, to a lesser extent, from the uranium and/or plutonium which has escaped fission. Additionally, the residues will usually contain some radionuclides as a result of "neutron capture" by other weapon materials. Still another source of residual nuclear radiation is the activity induced by neutrons[9] captured in various elements present in the explosion environment.

All of the nuclear radiation discussed thus far in this section is the result of fission reactions. As the student will recall, there are no fission products associated with the fusion reaction. Rather, neutrons are the only significant nuclear radiations produced in pure fusion reactions. Thus, it can be seen that for explosions in which both fission and fusion (thermonuclear) processes occur, the proportions of specific radiations will differ from those of typical fission explosions. However, for present purposes, the difference may be disregarded.

As the height of burst of a nuclear explosion occurs nearer the surface of the earth (or sea) larger and larger proportions of the earth (or water) enter the fireball and are fuzed or vaporized. When sufficient cooling has occurred, the fission products become incorporated with the earth particles as a result of the condensation of the vaporized products into fuzed particles of earth, etc. As the violent disturbance due to the explosion of the nuclear weapon subsides, these contaminated particles fall gradually back to the earth. This effect is referred to as the FALLOUT. The extent and nature of the fallout can range between wide extremes—dependent on the energy yield and design of the bomb, the height of the explosion, the nature of the surface beneath the point of burst, and the meteorological conditions. In the case of an AIR BURST occurring at an appreciable distance above the earth's surface, so that no large amounts of dirt (or water) are sucked into the cloud, the inherent radiation will be widely dispersed. On the other hand, a nuclear explosion occurring at or near the earth's

[5]Bomb, as it is used here, refers specially to the fissionable material in the nuclear weapon.

[6]In an analogous manner, ALPHA PARTICLES are also expelled as the result of the natural decay of the uranium (or plutonium) which has escaped fission in the explosion.

[7]This arbitrary amount has its origin with the classic 20-KT air burst, where because of the height of burst and the range of nuclear radiation, there are no significant radiological effects after one minute of time. For nuclear weapons of higher energy, the range over which the gamma rays are effective will be larger than that for the 20-KT air burst, but the rate at which the atomic cloud rises is higher. The converse is true for bombs of lower energy, so that the period over which the initial nuclear radiation extends may be taken as essentially the same—approximately one minute, irrespective of the energy release of the bomb.

[8]It should be noted that, although alpha and beta particles are present in the initial radiation, they are not considered significant for they are so easily absorbed. They will not reach more than a few yards, at the most, from the atomic cloud.

[9]Radioactivity induced by gamma rays from a nuclear explosion is either insignificant or completely absent.

surface can result in SEVERE contamination by the radioactive fallout.

It should be understood that fallout is a gradual phenomenon extending over a period of time. There can be considerable fallout—many hours after the surface detonation of a nuclear weapon, and many miles away. Additionally, there is a phenomenon called WORLD WIDE FALLOUT which occurs for years after a nuclear explosion. Fallout that occurs within 24 hours of a nuclear explosion is referred to as LOCAL FALLOUT

Fission products, which make up the greatest hazard in residual radiation, are initially very radioactive. However, this activity falls off at a fairly rapid rate as the result of decay. Figure 14D8 shows the exponential rate of decay of fission products after a nuclear explosion.

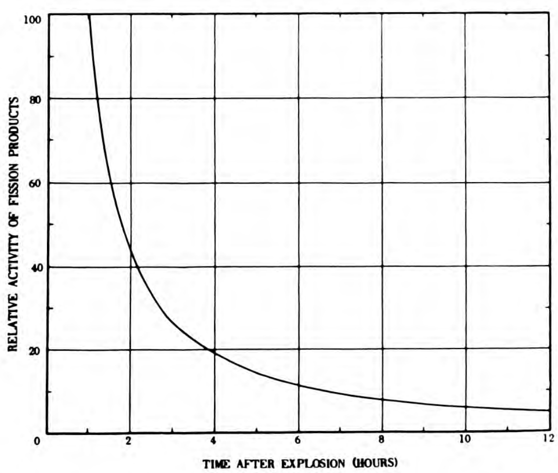


Figure 14D8.—Rate of decay of fission products after a nuclear explosion.

The RADIOLOGICAL EFFECTS from a typical AIR BURST are completely overshadowed by the effects of blast and thermal radiation. An exception to this would be a "low" air burst of a high yield weapon where there would be extensive induced radioactivity in the vicinity of ground zero. Radiological effects might also be of some consequence to those persons shielded from the primary causes of casualties.

A SURFACE BURST nuclear explosion presents an entirely different picture. With a surface burst, even though the induced activity will be considerable, the activity of the FALLOUT will be of so much greater consequence that the former may be neglected in comparison

The surface burst causes large amounts of earth (water), dust, and debris to be taken up into the fireball in its early stages. Here they are fuzed or vaporized and become intimately mixed with the fission products and other bomb residues. As a result there is formed, upon cooling, a tremendous number of small particles contaminated to some distance below their surfaces with radioactive matter. In addition, there are considerable quantities of pieces and particles, covering a range of sizes from large lumps to fine dust, to the surfaces of which fission products are more or less firmly attached.

The larger (heavier) pieces, which will include a great deal of contaminated material scoured and thrown out of the crater, will not be carried up into the mushroom cloud, but will descend from the column. Provided the wind is not excessive, these large particles, as they fall, will form a roughly circular pattern around ground zero (though the circle will be somewhat eccentric as the result of any wind). Most of this heavier material referred to above will descend within an hour or so.

The smaller particles present in the atomic cloud will be carried up to a height of several miles, and may spread out some distance in the mushroom cloud before they begin to descend. The actual time taken to return to the earth, and the horizontal distance traveled, will depend upon the original height attained, the size of the particles, and upon the wind in the upper atomsphere.

The fraction of the total radioactivity of the bomb residues that appears in the fallout depends upon the extent to which the fireball touches the surface. Thus, the proportion of available activity increases as the height of the burst decreases and more of the fireball comes in contact with the earth (or water). In the case of a "contact burst," some 50% of the total residual radioactivity will be deposited on the ground within a few hundred miles of the explosion. The remainder of the activity will remain suspended for a long period of time as with an air burst.

As a general rule, the pattern of contamination will be as illustrated in figure 14D9. Of course this pattern will vary with the wind velocities and directions at all altitudes between the ground and the height of the atomic cloud.

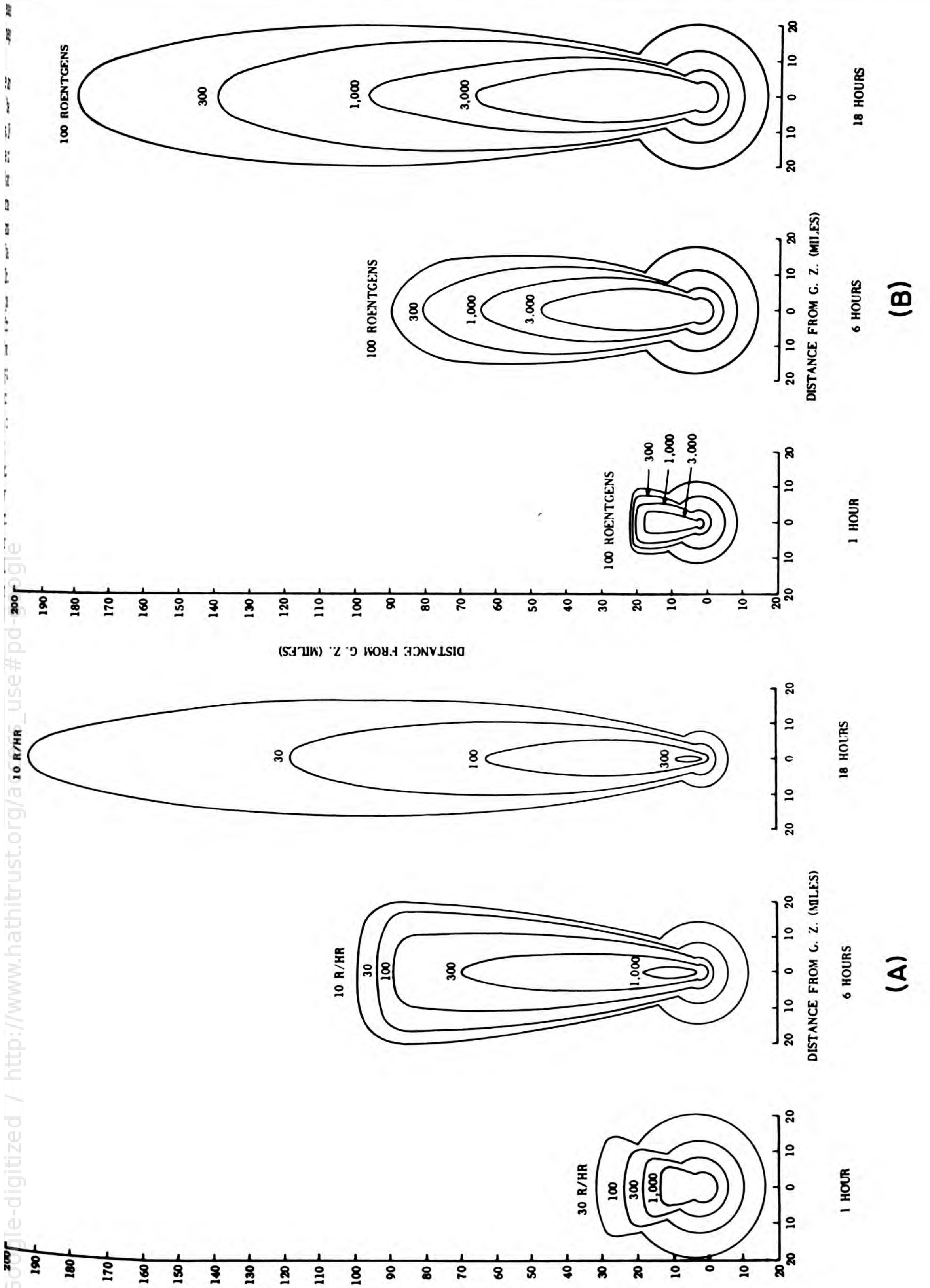


Figure 14D9.—a. Dose rate contours from fallout at 1, 6, and 18 hours after a surface burst of a nuclear weapon in the megaton range (115 mph effective wind); b. total accumulated dose contours from fallout at 1, 6, and 18 hours after a surface burst with fission yield in the megaton range (115 mph effective wind).

Note that the areas downwind are not immediately contaminated. Rather, most of the downwind area will not be seriously contaminated until hours after the explosion. For an example (fig. 14D9a), a location 32 miles downwind will have a DOSE RATE of about 30 roentgens/hour one hour after the detonation. At 6 hours, the dose rate has increased to 800 r/hr. Finally at 18 hours, it is down to roughly 200 r/hr. The increase in dose rate from 1 to 6 hours means that fallout was not complete at 1 hour after the explosion. With respect to the ACCUMULATED DOSE received, figure 14D9b shows that at one hour, the stipulated point will not have received any appreciable radiation because the fallout has only started to arrive. While at the end of 6 hours, the total dose has reached over 3000 roentgens. In general then, at any given location, at a distance from a surface burst, some time elapses before the fallout arrives.

Although the example given above is for the surface burst of a high fission yield nuclear weapon, the fallout phenomena associated with a low fission yield weapon are essentially the same except for differences in degree. Thus, a high energy fission yield explosion will mean a larger area contaminated to a more serious extent than would a low fission yield weapon.

The extent of residual radiation accompanying an UNDERGROUND BURST will depend primarily on the depth of burst and the weapon yield. With regards to initial radiation, it is either non-apparent or inconsequential by comparison to the residual radiation.

If the explosion occurs at sufficient depth below the surface, essentially none of the bomb residues and neutron-induced radioactive materials will escape to the atmosphere. There will be no appreciable fallout.

On the other hand, if the burst is near the surface so that the ball of fire actually breaks through, the consequences as regards fallout will not vary greatly from those of a surface burst. Other circumstances being more or less equal, the contamination in the crater area following an underground burst will be about the same as for a surface explosion of equal fission yield. However, the total contaminated area for a shallow underground burst will be greater because of the larger amount of fission products present in the fallout.

Radiological effects of UNDERWATER BURSTS closely parallel those of underground origin. The base surge, consisting of a contaminated cloud or mist of small water droplets also has a parallel in the underground phenomena. It is interesting to note that experts are placing lesser significance on the base surge as a source of contamination. It is now felt that though the base surge will materially contribute to the overall contamination, "rain-out" from the atomic cloud is of more consequence.

An important difference between an underwater burst and one occurring under the ground, is that the radioactivity remaining in the water is gradually dispersed, whereas that in the ground is not. Therefore, as a result of diffusion of the various bomb residues, mixing with large volumes of water outside the contaminated area, and the natural decay, the radiation intensity of the water in which a nuclear explosion has occurred will decrease fairly rapidly. Additionally, fission products will settle to the bottom of the body of water, thus greatly attenuating the radiological hazards.

Of specific naval interest is the fact that, after being distilled, contaminated sea water is perfectly safe for drinking. This is because the radioactive material remains behind in the residual scale and brine of the distillation process. It should be emphasized, however, that the mere boiling of water is of no value as regards the removal of radioactivity.

As the student will recall from chapter 12, the injurious effects of nuclear radiation represents a phenomenon completely absent in conventional explosions. For this reason, the subject of RADIATION INJURY will be discussed here in more detail.

The harmful effects of radiation appear to be due to the ionization (and excitation) produced in the cells that make up living tissue. As a result of ionization, some of the constituents that are essential to normal functioning are damaged or destroyed. Some of the products formed may act as cell poisons. Additionally, the living cells are frequently unable to undergo mitosis, so that normal cell replacement is inhibited.

The effects of nuclear radiations on living organisms depend not only on the total dose, that is, on the amount absorbed, but also on

the rate[10] of absorption, i.e. on whether it is ACUTE or CHRONIC. In an acute exposure, the whole radiation dose is received in a relatively short period of time. It has somewhat arbitrarily been defined as that dose received during a 24-hour period. Delayed radiations, like those which may be received from fission products, persist over a longer period of time and this type of exposure is of the chronic type.

The distinction between acute and chronic exposure lies in the fact that, if the dose rate is not too high, the body can achieve partial recovery from some of the consequences of the nuclear radiations while still exposed. In addition to the above, the percent of body exposure has significance. It follows then, that whereas a person would most probably die as the result of acute exposure of 700 roentgens whole-body radiation, he would probably suffer no critical effects if the dose were spread over a year—or if it were localized to a hand or foot.

The data provided in tables 14D3 and 14D4 are also plotted in figure 14D10. Each shows the effects of acute, whole-body radiation.

It can be noted in both the tables and the illustration that a particular effect is associated with a range of exposure doses. The reason for this uncertainty is that there are many factors, some known and some unknown, which determine the effect on the body of a specified

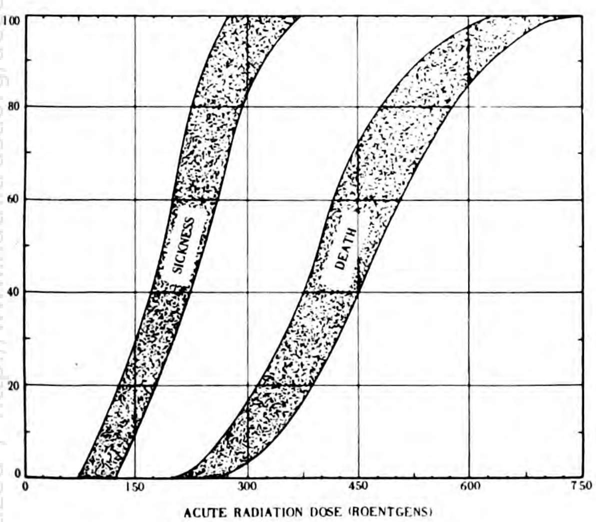


Figure 14D10.—Incidence of sickness and death due to acute exposure to various doses of nuclear radiation.

Table 14D3.—Expected Effects of Acute Whole-Body Radiation Doses

Acute dose (roentgens)	Probable effect
0 to 50	No obvious effect, except possibly minor blood changes.
80 to 120	Vomiting and nausea for about 1 day in 5 to 10 percent of exposed personnel. Fatigue but no serious disability.
130 to 170	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 percent of personnel. No deaths anticipated.
180 to 220	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 50 percent of personnel. No deaths anticipated.
270 to 330	Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20 percent deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months.
400 to 500	Vomiting and nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50 percent deaths within 1 month; survivors convalescent for about 6 months.
550 to 750	Vomiting and nausea in all personnel within 4 hours from exposure followed by other symptoms of radiation sickness. Up to 100 percent deaths; few survivors convalescent for about 6 months
1000	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
5000	Incapacitation almost immediately. All personnel will be fatalities within 1 week.

radiation exposure dose. For in addition to the biological variations among individuals, there are such considerations as the ages of exposed personnel and their state of health, depth of penetration into the body and the organs absorbing the radiation, and the orientation of the body with reference to the source of the

[10] A few radiation phenomena, such as the genetic effects, apparently depend on only the total dose received and are independent of the rate of delivery.

Table 14D4.--Summary of Clinical Symptoms of Radiation Sickness

Time after exposure	Survival improbable (700 r or more)	Survival possible (550 r to 300 r)	Survival probable (250 r to 100 r)
1st week	Nausea, vomiting and diarrhea in first few hours.	Nausea, vomiting, and diarrhea in first few hours.	Possibly nausea, vomiting, and diarrhea on first day.
	No definite symptoms in some cases (latent period)	No definite symptoms (latent period)	No definite symptoms (latent period)
2nd week	Diarrhea Hemorrhage Purpura* Inflamation of mouth and throat Fever Rapid emaciation Death (Mortality probably 100 percent)	Epilation* Loss of appetite and general malaise Fever	
3rd week		Hemorrhage Purpura Petechiae* Nosebleeds Pallor Inflamation of mouth and throat Diarrhea Emaciation	Epilation Loss of appetite and malaise Sore throat Hemorrhage Purpura Petechiae Pallor Moderate emaciation Diarrhea
4th week		Death in most serious cases (Mortality 50 percent for 450 roentgens)	Recovery likely in about 3 months unless complicated by poor previous health or superimposed injuries or infections

*See glossary

radiation (possible shielding of one part of the body with another).

A further matter of note is that the sooner the symptoms of radiation sickness appear after exposure, the more serious the consequences will be. Additionally, there is a latent period between the first symptoms of radiation exposure and a further condition of sickness.

E. Atomic Warfare Defense

14E1. General

Foresightedness and an understanding of the effects of nuclear weapons will have great bearing on survival in event of nuclear warfare. In general, there are two broad categories of protection that can be used to avoid the stunning effects of nuclear weapons. They are DISTANCE and SHIELDING. In other words, it is necessary to get beyond the reach of the effects, or to provide protection against them within their radii of damage.

The naval forces afloat have a distinct advantage in that they are readily dispersible. In addition to this, the ships of the Navy are so designed that they are comparatively resistant to the blast (and/or shock) and the thermal effects of nuclear weapons. Too, the features built into Navy ships for protection against gas attacks provide some measure of protection against radiation hazards.

Both long- and short-range preparation goes into proper readiness of Navy ships. Strict specifications are set for the designers and builders in order that the ships are as resistant as feasible to the effects of nuclear weapons. Command action is taken to keep fire and missile hazards minimized. Tactics include such things as greater than normal dispersal, the placing of all possible personnel under cover, establishing the highest state of material readiness, and the activation of WATER WASHDOWN systems.

After a nuclear explosion, the primary problem is to keep and/or return the particular ship to a maximum state of readiness by preventing the avalanching casualties resulting from secondary effects, by restoring normal services or rigging alternate (or emergency) services, attending to the wounded, conducting radiological surveys and decontaminating or localizing as applicable, and by assessing the extent and nature of damage and restoring the unit as nearly as possible to its original condition.

Tactics included after a nuclear explosion would include maneuvering to avoid, or minimizing the transit time through, any base surge, fallout areas, or radioactive waters.

Ashore, the military must also plan to disperse and/or provide suitable protection for personnel and material. The civil defense authorities should plan accordingly for the civilian population. Much can be done towards reducing blast and fire hazards in existing structures. Shelters and shelter areas can be provided. Disaster teams can be organized and trained to keep losses to a minimum.

14E2. Protective measures—individual action

For an individual, in the event of a surprise attack, proper and immediate action can mean the difference between life and death.

From experience gained in both nuclear and conventional explosions, there is little doubt that as a general rule it is more hazardous in the open than inside a structure. In an emergency, therefore, the best available shelter should be taken.

Aboard ship, TAKE COVER should be directed at the appropriate time for those in exposed stations. Once properly shielded, and other operations permitting, personnel should take a position with knees flexed, and with a firm grip on a substantial piece of the ship's structure. This position should be held until passage of the blast and/or the shock wave.

Ashore, civil defense authorities (or military, where they have jurisdiction) should have designated shelter areas and/or shelters. Subways would provide a good emergency shelter; however, these are found in only a limited number of cities. As an alternative, the basement of a building should be chosen. In this connection, a fire-resistant, reinforced-concrete or steel frame structure is to be preferred, since there is less likelihood of a large debris load on the floor above the basement. Even basements of good buildings are not, however, an adequate substitute for a well designed shelter.

Should there not be any opportunity to take the best shelter, alternate immediate action will be necessary. The first indication of an unexpected nuclear explosion (other than a subsurface explosion) would be a sudden increase in the general illumination. It would be imperative to avoid the instinctive tendency to look at the source of light, but rather to do everything possible to cover all exposed portions of the body (another reason for proper and suitable battle dress). A person inside a building should immediately fall prone and crawl behind a table or desk. This will provide a partial shield against splintered glass and other flying missiles. No attempt should be made to get up until the blast wave has passed, as indicated by the breaking of glass, cracking of plaster, and other signs of destruction. The sound of the explosion also signifies the arrival of the blast wave.

A person caught in the open by the sudden brightness due to a nuclear explosion, should drop to the ground, while curling up to shade the arms, hands, neck, and face with the clothed body. Although this action will have little effect against the initial nuclear radiation, it may help in reducing flash burns due to the thermal radiation. Of course, the degree

of protection from thermal effects will vary with the energy yield of the explosion. For as you will recall, low yield weapons expel all their thermal radiation in a short interval of time, while the higher the yield, the longer the thermal pulses of energy will last. Nevertheless, there is nothing to be lost, and perhaps much to gain through such action. The curled-up position should be held until after the blast wave has passed.

If a shelter of some kind, no matter how minor, e.g. in a doorway, behind a tree, or in a ditch or trench, can be reached within a second, it may be possible to avoid a significant part of the initial nuclear radiation, as well as the thermal radiation. But shielding from nuclear radiation requires considerable thickness of material and this may not be available in the open. By dropping to the ground, some little advantage may be provided by the ground and surrounding objects.

14E3. Protection from fallout

Protection against the residual radioactivity present in LOCAL FALLOUT presents a number of difficult and involved problems. This is because the radioactive products are not normally visible[11] and require radiac equipment for detection and measurement, and because of the widespread and persistent character of the fallout, and too, because fallout prediction is a function of complicated meteorological processes.

Ships will have to depend on proper maneuvers, the GAS TIGHT ENVELOPE, water wash-down systems and decontamination procedures for protection. Ashore, the civil defense and/or military authorities must be depended on for any evacuation of contaminated areas. Radiological surveys must be made to ascertain the extent and nature of the contamination. Once this is known, it is possible to take other corrective actions, such as orderly evacuation of sheltered survivors and decontamination of essential areas or equipments. Shifting winds and other unknown variables complicate any prediction of safe evacuation routes. A person may leave a comparatively safe location and end up the loser for his effort.

Of the passive protective measures that can be taken, shelter is the foremost. Where approved shelters are not available, even the basement of a frame house can attenuate nuclear radiation by a factor of about 10. Greater reduction is possible in large buildings or in shelters covered with several feet of earth. Three feet of earth will provide a radiation attenuation factor in the neighborhood of 1000.

F. Employment of Nuclear Weapons Effect

14F1. General

Many factors enter into the selection of the burst height (or depth) and yield of a particular weapon. Among these are fusing limitations, available delivery systems, and the degree of damage desired.

From an EFFECTS standpoint, the basic criteria which govern weapon selection are peak blast wave overpressure, peak dynamic pressure, duration of the positive wave (of blast wave), crater extent, thermal radiation, initial nuclear radiation, residual fission product fallout, and induced ground contamination.

The actual mechanics of weapon selection is a very complex operation. This operation is the function of relatively high echelons of command. The student should be aware that there also are great moral and political issues involved in the use of nuclear weapons. For these reasons, the actual committing of nuclear weapons to use by our country is the responsibility of the President of the United States. Notwithstanding, some generalized statements concerning the relative importance of various effects for different burst conditions is considered essential to a complete orientation in the nuclear weapons subject area.

[11] Although there are cases on record, where the fallout was visible as a white powder or dust, different circumstances would probably have made it impossible to see the fallout.

14F2. Surface burst

A SURFACE BURST will increase the range at which peak overpressures greater than about 12 psi occur. It will reduce thermal radiation received by ground targets compared to that received from an air burst at the same slant range and it will produce significant cratering and ground shock. A peak overpressure of 12 psi will cause severe damage to all structures except those of reinforced-concrete, blast-resistant construction. It will also cause moderate to severe damage to most military equipments. Most naval ships operating today will receive moderate damage (immobilization) when subjected to 20 psi peak air overpressure. Five psi will cause light damage to all naval and mercantile shipping. Light damage to naval ships consists of damage to electronic, electrical, and mechanical equipments—however the ships may still be able to operate effectively.

The surface burst will overdestroy some area. It is therefore not as economical (in its damage capabilities) as an air burst. Conceivably, therefore, the surface burst would be used against resistant targets or where assured destruction is desirable.

The LOCAL FALLOUT associated with a surface burst is a very significant factor in nuclear weapons selection.

14F3. Air burst

An AIR BURST will increase the ground range at which overpressures of about 10 psi or less are obtained; maximize areas at which significant thermal radiation is received on the ground; and eliminate local fallout contamination. Windowpane breakage is associated with 0.5 psi overpressure, while severe damage to wood frame houses occurs with 3 psi, and to reinforced-concrete buildings with approximately 10 psi[12].

Figure 14F1 accumulates certain cardinal damage criteria for air burst explosions.

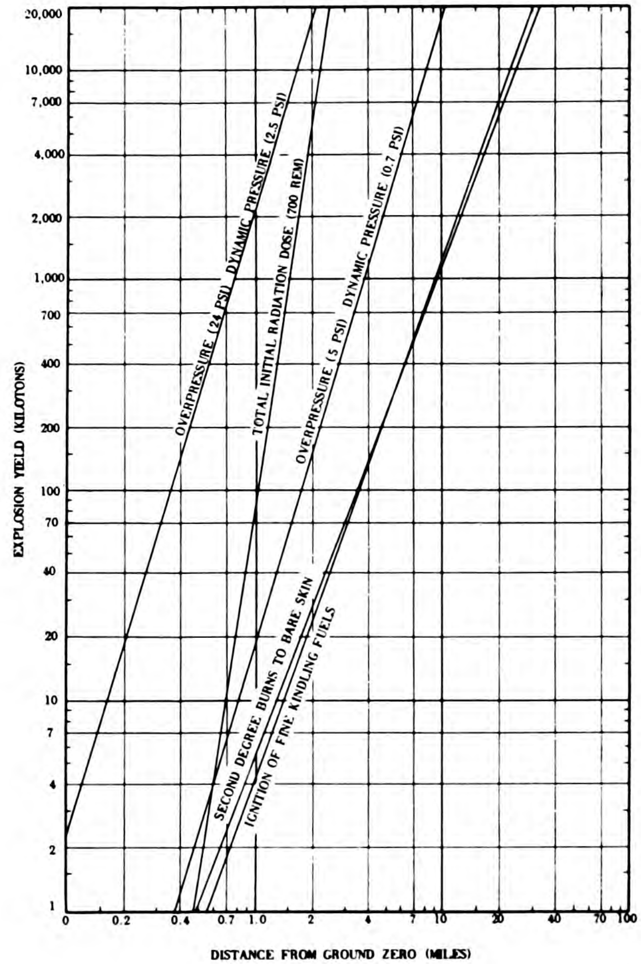


Figure 14F1.—Limiting distances from ground zero at which various effects are produced in an air burst.

14F4. Subsurface burst

With a SUBSURFACE BURST, peak air overpressure, thermal radiation, and initial nuclear radiation decrease as the depth of the burst is increased. Cratering, ground (or water) shock, and fallout contamination will increase with the depth of burst up to a maximum (the optimum depth depends on the effect being considered) and then decrease. Maximum water waves will be produced at a certain critical depth of burst.

[12]Because the degree of damage depends upon the duration of blast, the same structure would require 10.5, 9.5, and 9 psi overpressure with yields of 1 KT, 100 KT, and 10 MT, respectively.

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APPENDIX A

INTRODUCTION TO BASIC ELECTRICITY AND ELECTRONICS

A1. Introduction

A satisfactory understanding of guided missile principles requires some background in basic electricity and electronics. This appendix is intended to help those readers who do not have such a background. It is not a course in electricity or electronics; it deals only with elementary principles, and it does not go into them very deeply.

This appendix may be used for a quick review of electricity and electronics by the reader who has some familiarity with these subjects. It can be used without further study of these subjects to provide a minimum understanding of the material covered in this text. If time permits, the student with no electronics background should consult a textbook of basic electronics.

A2. Electrical nature of matter

In the structure of certain metallic atoms, some of the electrons are so loosely bound to the nucleus that they are comparatively free to move from one atom to another. A small amount of energy will cause some of these electrons to be removed from the atom and become free electrons. It is these free electrons that permit the flow of electric current in an electrical conductor.

Substances that permit the free motion of a large number of electrons are called CONDUCTORS. Copper is a good conductor because it has many free electrons. Another way of saying this is that a good conductor has low opposition or low RESISTANCE to current (electron) flow.

Some substances such as rubber, glass, and dry wood have very few free electrons. In these materials, large amounts of energy must be expended in order to break the electrons loose from the influence of the nucleus. These substances containing very few free electrons are called poor conductors, nonconductors, or INSULATORS.

Listed below are some of the best conductors and best insulators in the order of their ability to conduct or resist the flow of electrons.

CONDUCTORS	RESISTORS
Silver	Dry Air
Copper	Glass
Aluminum	Mica
Brass	Rubber
Zinc	Asbestos
Iron	Bakelite

One of the fundamental laws of electricity is that LIKE CHARGES REPEL EACH OTHER AND UNLIKE CHARGES ATTRACT EACH OTHER. In the storage battery, a source of electrical energy, electrons are emitted from the negative electrode externally, pass through some load, such as the starter in an automobile, and back to the positive electrode of the battery. (See fig. A1.)

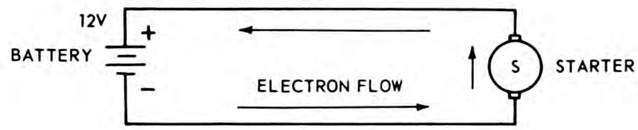

Figure A1.—Electron flow in a series circuit.

A3. Electric current

The drift or flow of electrons through the circuit is called an electric current. The term that defines unit current flow is the AMPERE. The usual symbol for current is I.

A flow of 1 ampere is equivalent to the flow of 6.28×10^{18} electrons per second past a fixed point in the circuit. The ampere can be considered analogous to the rate of flow of water through a pipe in gallons per second. A unit quantity of electricity is moved through an electric circuit when 1 ampere flows for 1 second. This unit is equivalent to 6.28×10^{18} electrons and is called the COULOMB. The commonly used symbol for coulomb is Q. The rate of flow of current in amperes and the quantity of electricity moved through a circuit are related by the common factor of time. Thus, the quantity of electric charge, in coulombs, moved through a circuit is equal to the product of current in amperes, I, and the duration of flow in seconds, t. Expressed as an equation

$$Q = It.$$

DIFFERENCE IN POTENTIAL. The force that causes free electrons to move in a conductor as an electric current is called (1) an ELECTROMOTIVE FORCE (emf), (2) a VOLTAGE, or (3) a DIFFERENCE IN POTENTIAL. The commonly used symbol for this force is E. When a difference in potential exists between two charged bodies that are connected by a conductor, electrons will flow along the conductor from the negatively charged body to the positively charged body until the two charges are equalized and the potential difference no longer exists.

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An analogy of this action is shown in figure A-2 where two water tanks are connected by a pipe and valve. At first the valve is closed and all the water is in tank A. Thus, the water pressure across the valve is maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water stops flowing in the pipe when there is no difference in water pressure between the two tanks.

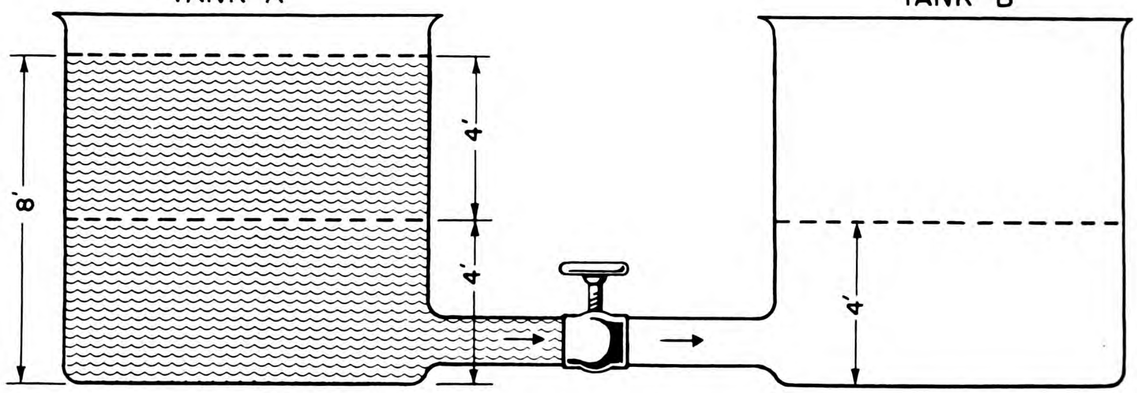

Figure A2.—Water analogy of difference in electrical potential.

Current flow through an electric circuit is directly proportional to the difference in potential across the circuit, just as the flow of water through the pipe in figure A-2 is directly proportional to the difference in water level in the two tanks. When a wire or other conductor is connected between a voltage source and a load, the voltage is propagated along the wire at the speed of light.

Another fundamental law of electricity is that the CURRENT IS DIRECTLY PROPORTIONAL TO THE APPLIED VOLTAGE (electrical pressure).

RESISTANCE. Electrical resistance (unit: the OHM) is that quality of an electric circuit that opposes the flow of current through it. The simple electric circuit in figure A-1 has resistance in varying degrees in all of its parts—that is, in the source, in the load, and in the connecting wires. The resistance of wire in common electrical circuits is negligible. However, in long transmission and power distribution lines, resistance is proportionally larger and must be taken into consideration.

Resistance to current flow through a conductor depends upon the (1) length of the wire, (2) diameter of the wire, and (3) material of the wire. So too in the water system analogy, resistance to the flow of water through a pipe depends upon the (1) length of the pipe, (2) the diameter of the pipe, and (3) the condition of the walls inside of the pipe.

Still another fundamental law of electricity is that the current is directly proportional to the applied voltage and inversely proportional to the resistance. This is Ohm's law. Its formula is:

$$I = \frac{E}{R} \text{ (Also: } E = IR;\ R = \frac{E}{I}\text{)}$$

where I is the intensity of the current in amperes, E the difference in potential in volts, and R the resistance in ohms. If any two of these quantities are known, the third may be found by solving the equation. For example, if the voltage across the load in figure A-3 is 120 volts and the effective resistance of the load is 20 ohms, the current through the load will be 120/20, or 6 amperes. If the effective resistance of the load remains constant at 20 ohms, then in accordance with Ohm's law the current will double if the voltage doubles, or halve if the voltage halves. In other words

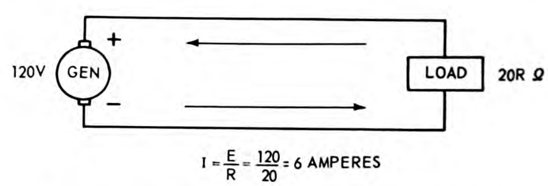

Figure A3.—Current in a simple series d-c circuit.

the current through the load will vary directly with the voltage across the load.

POWER. Power is the rate of doing work. In a d-c circuit, power is equal to the product of the voltage and current. Expressing the power (P) in watts, the current (I) in amperes, and the emf (E) in volts, the equation becomes

$$P = EI$$

or, expressed differently, power in watts delivered to a circuit varies directly as the square of the applied emf in volts and inversely with the circuit resistance in ohms.

Thus:

$$P = \frac{E^2}{R}$$

Still another way: power in watts varies directly as the product of the circuit current (in amperes) squared and the circuit resistance (in ohms). Thus:

$$P = I^2R$$

In figure A-3 there is a 120-volt potential across a load of 20 ohms resistance. By applying Ohm's law, we can find that 6 amperes of current is being drawn by the load. We can also find the power being delivered to the load, as follows:

$$P = EI = 120 \times 6 = 720 \text{ watts}$$

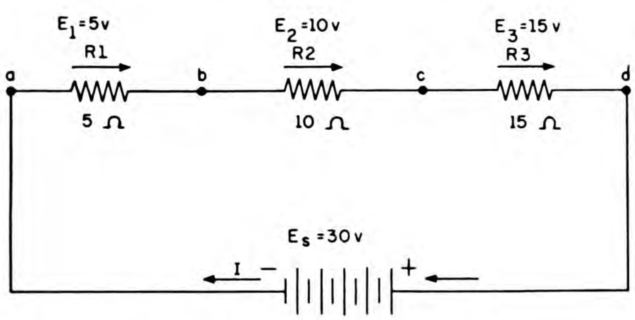

Figure A4.—Resistors in series.

If a circuit is so arranged that the electrons have only one possible path, the circuit is called a SERIES CIRCUIT (fig. A-4). Resistances in series are added, thus the total resistance in the illustration is $R_t = R1 + R2 + R3 = 5 + 10 + 15 = 30$ ohms. By applying Ohm's law, $I = E/R$, and using the values shown in the circuit (fig. A-4), $I = 30/30 = 1$ ampere. This same current of 1 ampere flows through R1, R2, and R3, because there is only one path for the current to follow. Notice that the path of electron flow is away from the negative terminal of the battery, around through the resistors, and back to the positive terminal. Since current is flowing through each resistor in the circuit there is a voltage drop across each resistor that is equal to the product of the current, in amperes, times the value of each resistor, in ohms. Since $E = IR$, and the current is 1 ampere, then the voltage drop across R1 = 5 v, R2 = 10 v, and R3 = 15 v. The sum of the voltage drops is equal to the applied voltage E_s.

OHM'S LAW APPLIED TO PARALLEL CIRCUITS. The parallel circuit differs from the simple series circuit in that two or more resistors, or loads, are connected directly to the same source voltage. Therefore, there is more than one path that the electrons can take. The more paths (or resistors) that are added in parallel, the less total opposition there is to the flow of electrons from the source. In the series circuit the condition is opposite—the more resistances added, the greater the opposition to the flow of electrons. In both cases, current flows from the negative terminal of the source and returns to the positive terminal. Referring to fig. A-5, note that the current through each individual branch depends upon the source voltage and the resistance of that branch. The individual currents can be found by applying Ohm's law to each branch.

The total current, I_t, of the parallel circuit is equal to the sum of the branch currents. Total resistance R_t in a parallel circuit is smaller than the smallest resistance in the circuit—quite different from the series circuit where the $R_t = R_1 + R_2 + R_3$.

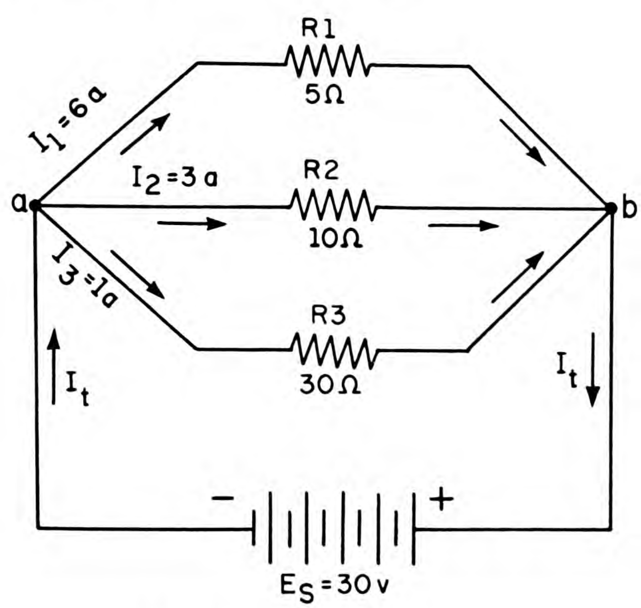

Figure A5.—Resistors in parallel.

In a parallel circuit the formula for R_t is:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}, \text{ etc.}$$

There is a special case where all resistors in a parallel circuit are of the same value. Then R_t can be found by taking the value of one resistor and dividing it by the total number of resistors in the circuit.

$$R_t = \frac{R \text{ (of one resistance)}}{\text{Numerical sum of resistances}}$$

Suppose all the resistors in figure A-5 were the same value:

$$R_1 = 2\Omega,\ R_2 = 2\Omega, \text{ and } R_3 = 2\Omega, \text{ then}$$

$$R_t = \frac{2}{3} = .66\Omega.$$

Another special case is where there are <u>two</u> resistors of different values. Then

$$R_t = \frac{R_1 R_2}{R_1 + R_2} = R_t = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2\Omega.$$

As in the series circuit, the total power consumed in a parallel circuit is equal to the power consumed in all the individual resistors.

SERIES-PARALLEL CIRCUIT. Series-parallel circuits are made up of a number of resistors arranged in numerous series-parallel combinations. In more complicated circuits, special theorems, rules, and formulas are used. These are based on Ohm's law and provide faster solutions for particular applications. Series formulas are applied to the series parts of the circuit, and parallel formulas are applied to the parallel parts. For example, in figure A-6, the total resistance, R_t, may be found in three logical steps.

First, R3, R4, and R5 in figure A-6a are in series (there is only one current path). They may be combined as in figure A-6b to give the resistance, R_s, of the three resistors. Thus,

$$R_s = R_3 + R_4 + R_5 = 5 + 9 + 10 = 24 \text{ ohms}.$$

This is in parallel with R2 (because they both receive the same voltage).

Second, the combined resistance of R_s in parallel with R_2 (fig. A-6c) is

$$R_{s,2} = \frac{R_2 R_s}{R_2 + R_s} = \frac{8 \times 24}{8 + 24} = 6 \text{ ohms}.$$

Third, the total resistance, R_t, is determined by combining resistors R1 and R6 with $R_{s,2}$ as follows:

$$R_t = R_1 + R_6 + R_{s,2} = 2 + 12 + 6 = 20 \text{ ohms}.$$

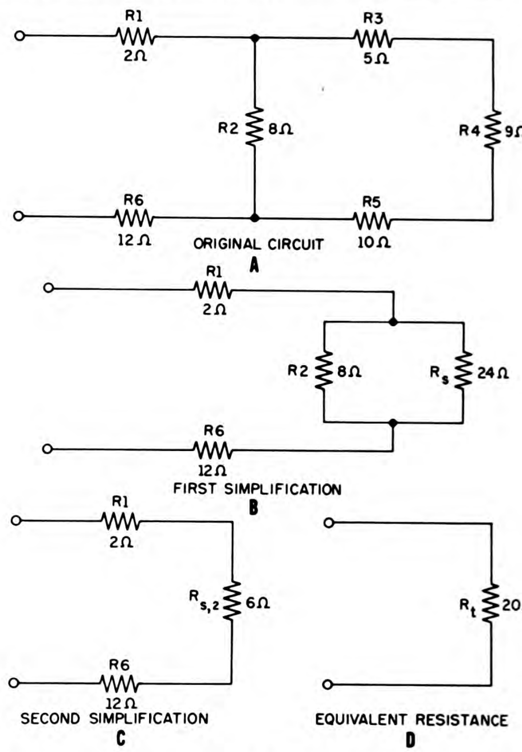

Figure A6.—Solving for total resistance in a compound circuit.

A4. Capacitance

Capacitors, sometimes called condensers, are devices that possess the property of capacitance. In their simplest form, capacitors consist of two metal plates that are separated by a dielectric (insulator). A capacitor stores free electrons when a voltage is impressed between the plates. In figure A-7a the capacitor C is uncharged. In figure A-7b, a battery is shown connected to the capacitor by means of a switch. When the switch is in position 1, electrons flow from the negative terminal of the battery to the left-hand plate of the capacitor, C. At the same time electrons are drawn away from the right-hand plate of the capacitor to the positive terminal of the battery, leaving it positively charged because of the deficiency of electrons. This action continues until the voltage across the capacitor equals the source voltage, at which time electrons cease to flow and the capacitor is said to be charged. The voltage across the capacitor opposes the source voltage (fig. A-7c).

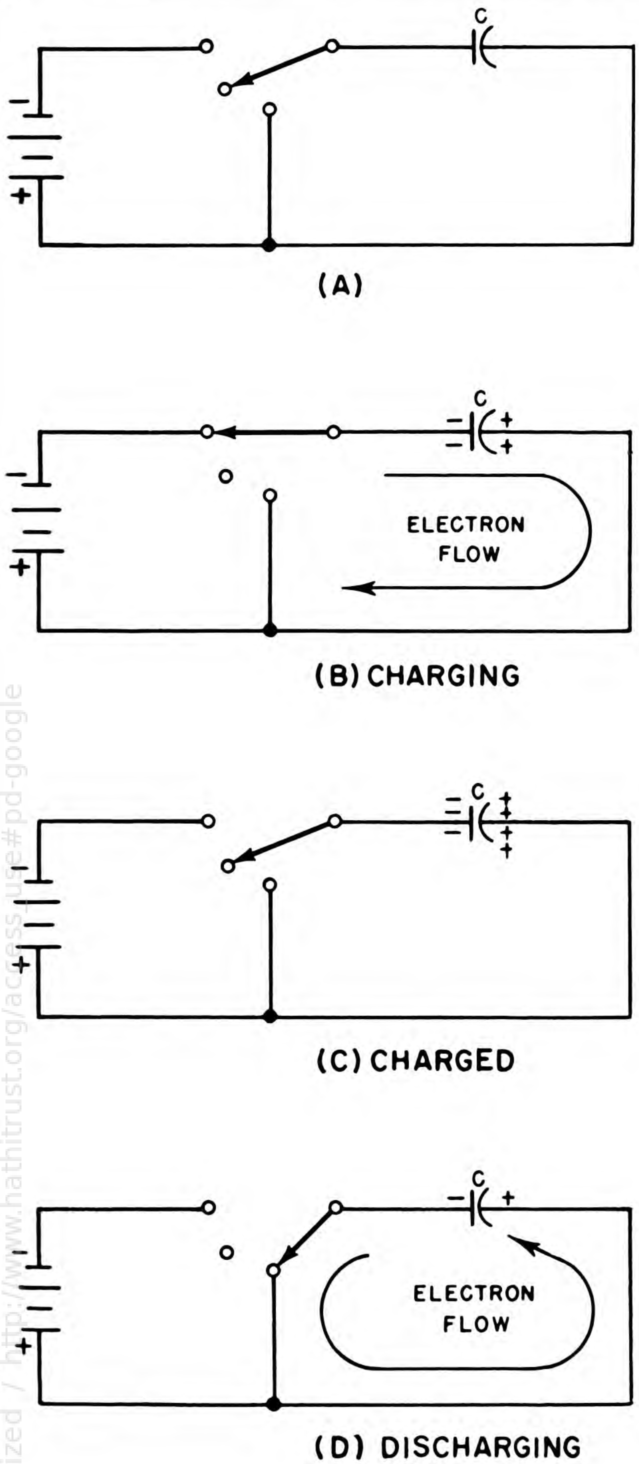

Figure A7.—Capacitor action.

In figure A-7d the switch has been moved to position 3, allowing the capacitor to discharge and return to its original state of equilibrium.

UNIT OF CAPACITANCE. Capacitance is the property of a capacitor to store electrical energy. A unit of capacitance is the farad. Practical units of capacitance are the microfarad (μf) and the micromicrofarad ($\mu\mu$ f).

The capacitance of a capacitor is proportional (1) directly to the area of the plates; (2) inversely to the distance between the plates; and (3) directly to the dielectric constant of the material between the plates.

Thus, it is evident that the capacitance increases when the area of the plates is increased, decreases when the distance between plates is increased and increases if the value of the dielectric constant is increased.

TIME CONSTANT. A capacitor cannot assume a charge instantaneously. It takes a definite time for a capacitor to become fully charged after a voltage is impressed across it. Even the capacitor in figure A-7 took some time to assume the charge. The actual time it takes a capacitor to become charged depends upon the values of the capacitor and the resistance in the circuit. Since connecting wires offer little resistance to the flow of electrons, their resistance can be neglected.

In figure A-8, a resistance has been placed in series with the capacitor, and this will have great effect on the time it takes the capacitor to become charged. The time constant (TC) of the circuit is equal to the resistance in ohms times the capacitance in farads. In figure A-8,

$$TC = RC = 1 \times 10^{-6} \times 1 \times 10^{6} = 1 \text{ sec.}$$

A capacitor charges and discharges exponentially. It will charge to 63% of the applied voltage in 1 TC. Therefore, in 1 second the capacitor in figure A-8 will have 63 volts across it, and in the second second it will add 63% of the remaining 37 volts. For most purposes, a capacitor may be considered fully charged after 5 time constants.

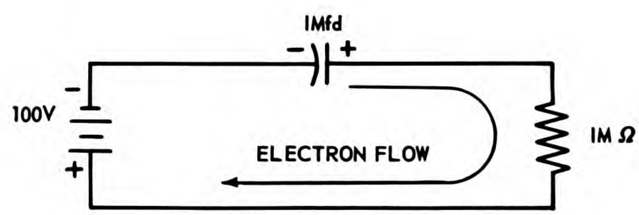

Figure A8.—RC time constant.

A5. Inductance

Whenever current is passed through a conductor a magnetic field is built up around it. The strength of the field is proportional to the magnitude of the current.

In figure A-9A, the battery terminals are connected by a wire that passes directly over a magnetic compass.

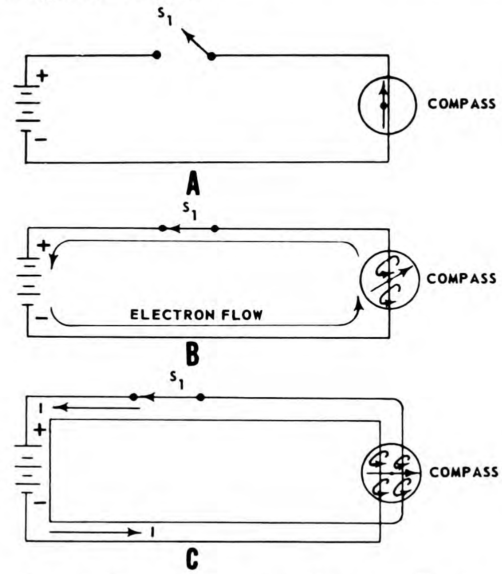

Figure A9.—Magnetism caused by current flow in a conductor.

Since the switch S1 is open, no current is flowing through the circuit, and the needle on the compass points toward magnetic north.

In figure A-9 the switch S1 is closed, completing the circuit, and current flows. As the result of this flow of current, an electromagnetic force is built up around the wire and causes the compass needle to deflect. The amount of deflection depends on the amount of current flowing through the conductor.

In figure A-9C, the wire between the battery terminals has been coiled so that two turns of wire pass over the compass. The same current is passing through both turns of wire and each wire has a magnetic field built up around it. The magnetic fields built up around the two individual wires reinforce one another, thus causing a greater deflection of the compass needle. The arrows around the conductors show the direction of the magnetic field surrounding the conductors.

Whenever two coils are placed in close proximity to one another, and one coil is connected to a source voltage, the current flowing through the energized coil will set up a magnetic field around that coil. The magnetic lines of force of the expanding field will also cut the windings of the second coil, and induce a momentary voltage in the second coil. This voltage will be opposite in polarity to the exciting voltage. This action, shown in figure A-10, is called mutual inductance. Mutual inductance is the principle used in transformer action.

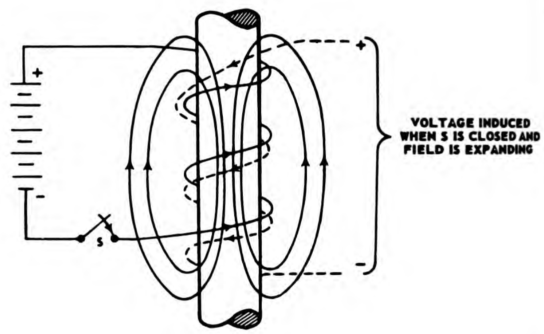

Figure A10.—Mutual inductance.

D-c is used with coils when the coils are used as part of a relay, or a similar device.

Whenever an alternating current, a-c is applied to a coil, the magnetic field builds in one direction and collapses, and then builds up in the other direction and collapses, etc. The rate at which the field does this is dependent upon the frequency of the applied voltage.

INDUCTIVE REACTANCE. In alternating current (a-c) circuits the current changes continuously, causing a continuous change in the magnetic field around an inductor. This induces a counter electromagnetic force in the coil that opposes the flow of alternating current. This opposition is known as REACTANCE, and since the opposition is caused by the coil or inductor, it is called INDUCTIVE REACTANCE.

Because an inductor opposes any change of current through it, the voltage across an inductor leads the current through it.

A6. A-c circuits

In alternating-current circuits, where there is no opposition to current flow other than pure resistance, the current and voltage rise and fall sinusoidally and are in phase with one another, as shown in figure A-11.

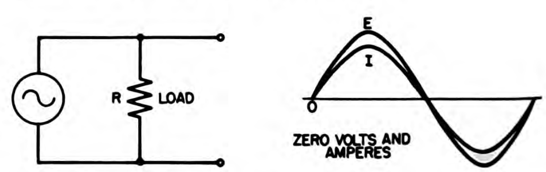

Figure A11.—Voltage and current phase relationship; resistive circuit.

When the voltage and current reach their maximum values (both positive and negative) at the same time, they are said to be in phase.

Should the a-c circuit be capacitive, there will be a phase shift between the voltage and current. If there were no d-c resistance in the circuit, the current charging the capacitor would lead the voltage across it by 90° (fig. A-12.

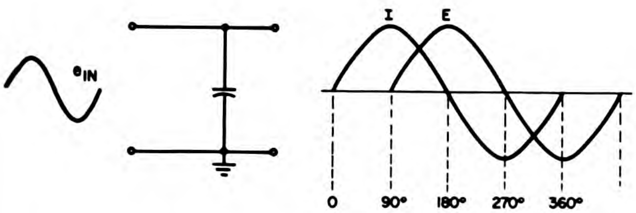

Figure A12.—Phase relationship; capacitive circuit.

In an a-c circuit containing inductance only (no resistance), since the inductance of a coil opposes any change of current through it, the voltage across the coil leads the current through the coil by 90° (fig. A-13).

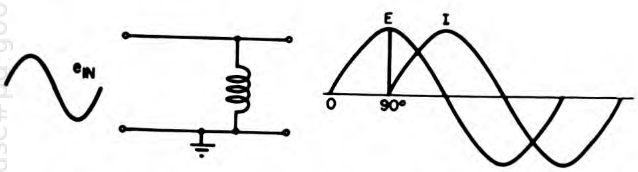

Figure A13.—Phase relationship; inductive circuit.

Since reactance of the capacitor (X_c) and the reactance of the coil (X_L) shift the relationship between voltage and current in opposite directions (I leads E in capacitive; E leads I in an inductive circuit), their effects on current and voltage are 180° out of phase with one another. It follows then that their respective oppositions will also be 180° out of phase. In alternating-current circuits, the a-c opposition to current flow is called impedance (symbol Z). Impedance is a combination of resistance, and inductive and capacitive reactance.

There can be no purely capacitive or inductive circuit, since the wires connecting the circuit have some d-c resistance. The coil and the capacitor also have some d-c resistance. Therefore, the phase shift between E and I across either circuit (figs. A-12 and A-13) would never be 90°—but something less, depending upon the value of R.

TUNED CIRCUITS—SERIES. In electronics, an important use of capacitors and inductors is in tuned circuits. It is the phase relation of the reactance (opposition) of the capacitor and inductor that make them so useful. For example, in figure A-14 a capacitor and coil are connected in series and are being excited by radio frequency (RF) energy.

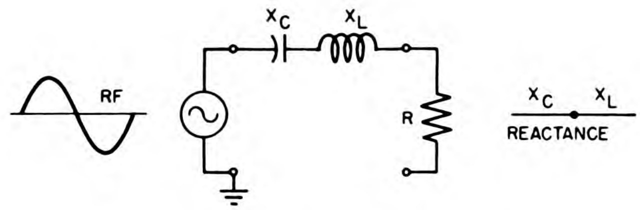

Figure A14.—Series-resonant circuit.

At a certain RF frequency, the reactance of the capacitor (X_c) and the reactance of the coil (X_L) will be equal in amplitude and opposite in phase, and will cancel each other out. Therefore, at this frequency the circuit appears resistive only and a signal will pass through readily. The frequency at which $X_c = X_L$ is known as the resonant frequency of the circuit. This may be established as follows:

At resonance

$$X_L = X_c; \qquad X_L = 2\pi f L;$$

where f = frequency in cycles per second, and L = inductance in henries. And

$$X_c = \frac{1}{2\pi f C}$$

where C = capacitance in farads. The resonant frequency = $1/2\pi\sqrt{LC}$.

In tuned circuits the inductor L and capacitor C may also be connected in parallel, as shown in figure A-15.

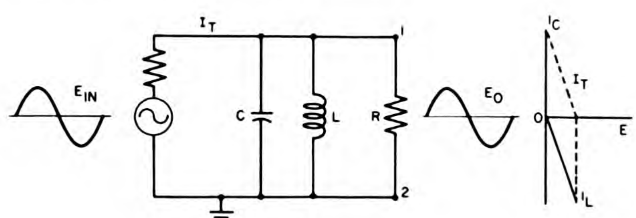

Figure A15.—Parallel-resonant circuit (tank circuit).

In figure A-15, the inductive branch of the circuit causes the current through it to lag the voltage across it by 90° (ideally). In the capacitive branch the current leads the voltage by 90° (ideally). The vector sum of currents in the circuit is effectively zero. Since there

is no current (ideally) flowing in the circuit at resonant frequency, it follows that this type of circuit must offer a high impedance (opposition) to current flow at resonance. Therefore, a signal of the resonant frequency can be picked off and passed on to a following stage.

$X_L = 2\pi fL$, therefore if f is increased, X_L increases and offers more opposition to current flow. $X_c = 1/2\pi fC$, and if f is increased, X_c decreases and the capacitive branch will offer less opposition to current flow. Therefore, an increase in frequency will be shorted to ground through the capacitive branch and a decrease in frequency will be shorted to ground through the inductive branch. Only at the resonant frequency will both branches offer the same opposition to current flow. When this occurs the circuit is said to be a tuned circuit. A signal at the resonant frequency can be picked off at leads 1 and 2 of figure A-15. All information and noise at other frequencies will be shorted to ground.

A7. Electron tubes

The electron vacuum tube is made up of a highly evacuated glass or metallic shell.

The electron tube can be made to (1) convert a-c to d-c, (2) amplify weak signals, and (3) generate frequencies much higher than any conventional generator.

Thermionic emission is the process by which electrons gain enough energy by means of heat to be released from the surface of the emitter in a vacuum tube. Thermionic emission is the type of emission most frequently employed in vacuum tubes.

DIODES. The simplest type of vacuum tube is the diode. It consists of two elements, a cathode (the emitter) and a plate (or anode). The cathode is heated by a filament (directly or indirectly).

DIODE OPERATION. Figure A-16 illustrates a diode consisting of plate (P), cathode (K), and a filament (F). The plate is connected through a resistor (R) to a supply voltage E_s. The direction of the arrows indicates the direction of current (electron flow) in the circuit.

The filament heats the cathode (coated with thorium) to a temperature that "boils off" electrons into the space between the plate and cathode. Electrons are negatively charged particles, and the plate is connected to the positive terminal of the battery. Since unlike charges attract, electrons (current) will flow from the cathode to the plate, through the resistor to the battery and back to the cathode. Current can flow in only one direction (from cathode to plate) in a diode, and it is this principle that makes a diode useful as a detector and a rectifier.

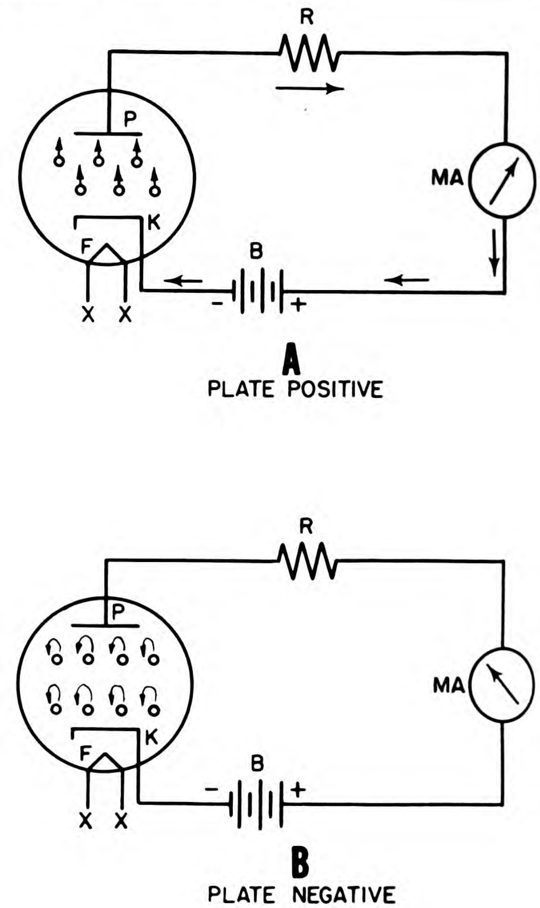

Figure A16.–Diode vacuum tube.

TRIODES. A third element (excluding filament) is introduced to make a triode. It is called a control grid, and is placed between the cathode and the plate (although nearer to the cathode).

The function of the grid is to control the flow of electrons from the cathode to the plate in much the same manner as the opening and closing of a water faucet controls the water coming from a spigot.

A small change in grid potential (voltage) causes a relatively large change in current (plate current) through the tube. Grid control of current is accomplished by the grid-to-cathode voltage relationship. If the grid to cathode voltage is increased sufficiently and the grid is negative with respect to cathode, current will stop flowing. This voltage that exists between grid and cathode is called the

BIAS voltage, and if this bias voltage is driven negative enough (with respect to the cathode voltage) the tube will cut off; the voltage between grid and cathode at this time is called the CUT-OFF-BIAS.

Figure A-17A, B, C, shows the effect of grid voltage on plate current, as read on the ammeter in the circuit shown.

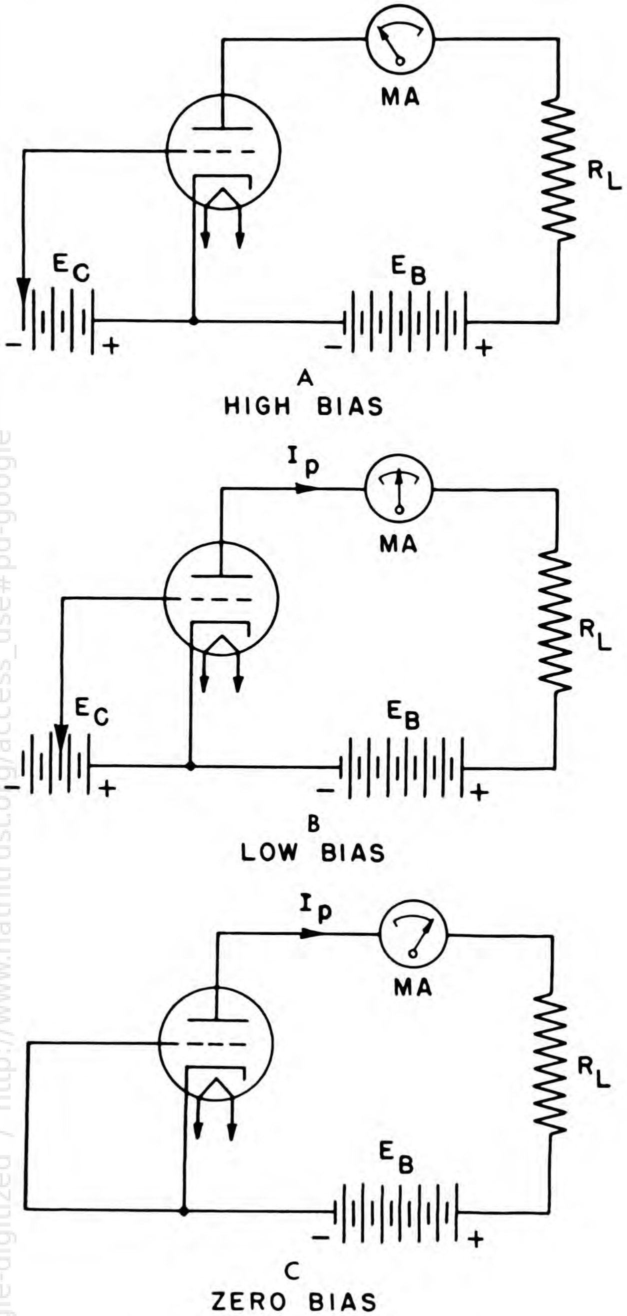

Figure A17.–Effects of grid bias.

When the negative bias is high (cut-off or higher) as shown in figure A-17A, no current flows because the negative voltage on the grid repels the electrons emitted by the cathode, and there is no current flow from cathode to plate.

In figure A-17B, the bias E_c is made less negative (the tap is moved toward the positive terminal of E_c), and electrons may now flow from cathode to plate.

In figure A-17C, the bias E_c, has been removed completely; the grid and cathode are at the same potential, and maximum current flows through the tube.

A triode can be used as a voltage amplifier, and if biased properly can reproduce any input signal with good fidelity (no distortion) and an increase in amplitude. To achieve this, the triode is biased between whatever the cut off bias is, and whatever zero bias is for the particular triode. Referring to figure A-18 it can be seen that E_o is an exact reproduction of the input E_{in}, as far as wave shape is concerned. But it has been increased in amplitude. A triode biased in this manner is a voltage amplifier. A triode voltage amplifier is used in audio work where good reproduction is especially important.

MULTIELEMENT TUBES. The introduction of additional elements in the vacuum tube has the effect of reducing the interelectrode capacitance between the elements, increasing the gain of the tube, and causes the tube to have a better or higher frequency response. Decreasing the physical size of the tube also results in a higher frequency response.

A8. Instruments

An AMMETER is an electrical instrument used to measure line current or current in any branch of a circuit. Due to the construction of an ammeter, caution must be taken when connecting the meter in a circuit. Always break the circuit at some convenient point and connect the meter in the break. RULE: Connect an ammeter in series and in proper polarity.

A VOLTMETER is an instrument used to measure supply voltage, or the voltage drop across any part or component in a circuit. RULE: Always connect a voltmeter across (in parallel with) the circuit being measured.

An OHMMETER is an instrument used to measure the resistance of a circuit or any part of the circuit. (CAUTION: Be sure all power is removed before connecting an ohmmeter in the circuit.) An ohmmeter is also used to test for circuit continuity.

A WATTMETER is an instrument used to measure power. It may be calibrated in watts for d-c, and either watts or decibels for a-c.

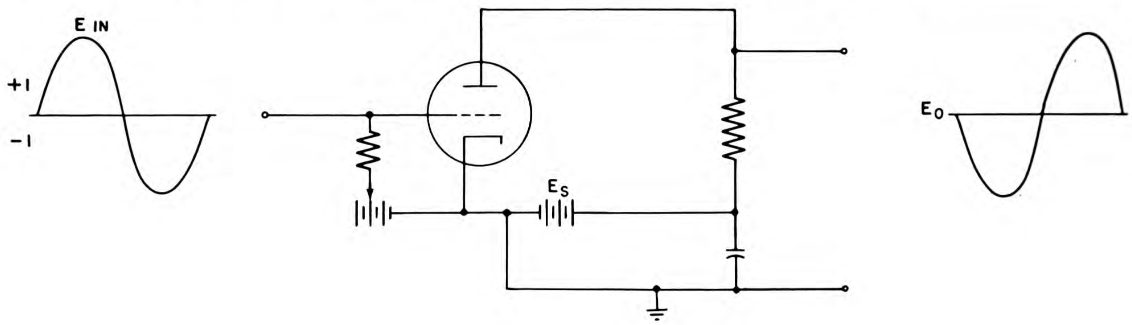

Figure A18.—Vacuum tube amplifier.

A WHEATSTONE BRIDGE is an instrument for measuring resistance very accurately. It can also be used to locate breaks in a circuit.

An OSCILLOSCOPE is an instrument used to show wave forms graphically, to measure voltage (d-c and a-c), to show the phase relationship between two signals, etc. By proper adjustment of the oscilloscope, a pictorial representation can be presented on the face of its cathode-ray tube of phase relations, and waveforms across components in electronic circuits. An oscilloscope is useful in trouble-shooting radio, TV, and radar equipment. It is also used in missile check-out procedures.

A signal generator is an instrument used to generate signals (as its name implies) in either the audio or RF range of frequencies. A signal generator is very useful in trouble-shooting radio, radar, and missile circuitry. Intelligence may be imposed on the signal from the generator, and this will cause the missile control surfaces to move the proper amount and direction. An appropriate signal generator, with associated equipment, may be classified as a flight simulator in the missile field.

A9. Power supplies

Most electronic devices having vacuum tubes (radio, radar, TV, etc.) require d-c voltage. But the most readily available power source is a-c. A power supply is a device containing a transformer (step-up), diodes, capacitor, and inductors, which rectify the a-c voltage to a d-c voltage.

A10. Oscillators

Vacuum tubes are also used for the generation of alternating voltages. When so used, they are called oscillators. Oscillators of this type are energy converters which change d-c electrical energy from the plate circuit power supply into a-c in the output circuit. In order to sustain oscillations, the circuit must have a positive feedback from the plate circuit. The tube in figure A-19 oscillates at a frequency determined by time constants of the circuit.

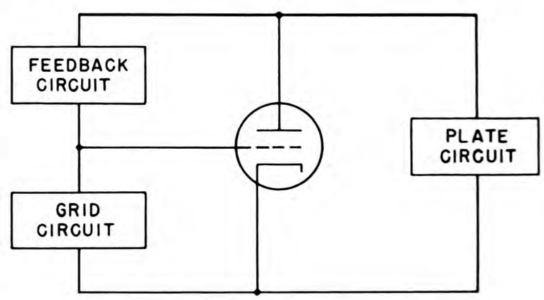

Figure A19.—Basic oscillator circuit.

Oscillators can be designed to generate frequencies from a few cycles per minute to billions of cycles per second. They can therefore be designed to cover the a-f (audio frequency) and r-f (radio frequency) bands. Oscillators are used in audio work and in radio and radar transmitters and receivers.

Sometimes it becomes necessary to generate signals other than conventional a-c signals, such as rectangular pulses and saw-tooth pulses. Specially designed oscillator circuits accomplish this.

A11. Radio

Four major components of a radio transmitter are: the oscillator (to generate radio frequencies), an amplifier (to amplify these oscillations), some means of adding intelligence to the RF (such as key for code signals, or a microphone for voice communication), and an antenna for radiating the RF and intelligence.

Figure A-20 shows the basic components of a transmitter. The function of the buffer in the illustration is to isolate the oscillator from the power amplifier in order to provide better frequency stability of the transmitter. It also provides a means for adding intelligence by modulating the carrier.

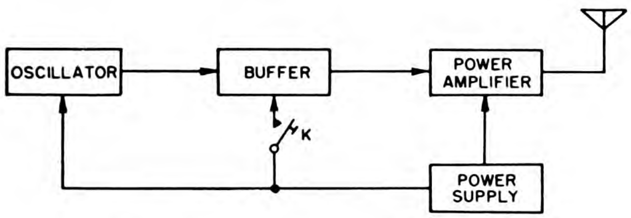

Figure A20.—Basic radio transmitter.

RECEIVERS are electronic devices used to receive transmitted r-f (with any superimposed intelligence), amplify the r-f carrier, and detect and amplify the intelligence. The superheterodyne receiver is the most commonly used type. Figure A-21 is a block diagram of such a receiver, showing the different stages necessary to detect and reproduce the transmitted intelligence.

A12. Radar

RADAR is a means of RAdio Detection And Ranging. A radar detects the presence of objects such as airplanes and ships, in darkness, fog, or storm. In addition to detecting their presence, radar can determine their bearing, range, and elevation, and enable the operator to recognize the general character of the radar target.

Radar is divided into three classifications: (1) surface and air search, (2) fire control, and (3) identification. Search radars are used generally in navigation and early-warning networks.

Fire control radar is used with certain types of gun batteries and missile batteries.

Identification radars are used in IFF (identification, friend or foe) and are used to identify our own and friendly ships and aircraft detected by radar.

The operation of radar is much the same as radio transmitting and receiving, except that the radar receiver is at the same location as the transmitter. The radar transmitter and receiver use the same antenna. This is done by the use of a duplexer in the antenna system. The duplexer is a high-speed electronic switch that can switch the antenna back and forth between transmitter and receiver at rates up to several thousand times a second.

The radar transmitter transmits a pulse of energy. The radiated pulse travels through space, hits a target, and is reflected. This reflection is known as the echo. The reflected echo travels back through space to the radar antenna and into the receiver.

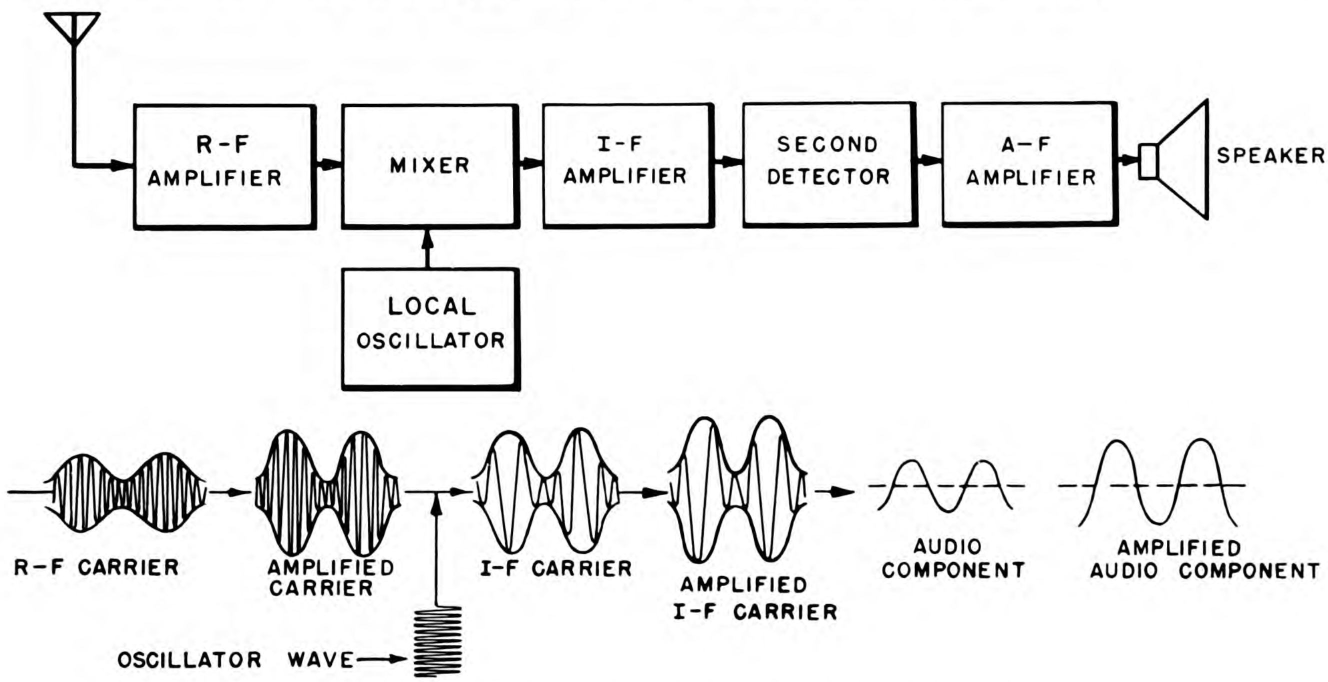

Figure A21.—Basic superheterodyne radio receiver and waveforms.

Since r-f energy travels at the speed of light (186,000 miles per second), it is easy to determine the range to a target as a function of time. It takes an r-f pulse of energy 1 μ sec (1 millionth of a second) to travel 328 yards.

Suppose that a target is at a range of 164 yards. The r-f energy will travel 164 yards to the target and 164 yards back to the receiver, a total of 328 yards. Therefore, the presentation on a cathode-ray tube would indicate that the target is 1 microsecond away. The scope can be calibrated to show the range in yards.

Figure A-22 shows a type of presentation used to determine range. This type of presentation is called the A-type. The radar, when it transmits, triggers the scope generating the sweep and main bang. Later, while the transmitter if off, an echo will appear on the face of the scope some distance away from the main bang or radar reference.

If the antenna is directional and is moved in azimuth and elevation, then indications of azimuth and elevation may be shown on a different type of scope presentation.

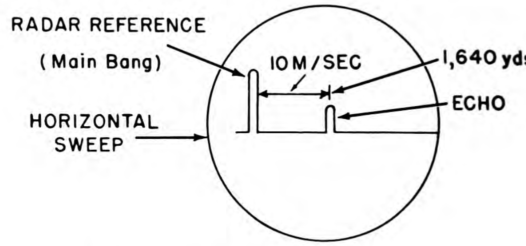

Figure A22.—Radar "A" scope presentation.

APPENDIX B
GLOSSARY
Introduction

This glossary is intended as a convenience for the student. It explains briefly those technical terms used in this textbook that the student should be acquainted with in order to comprehend the subject matter. The explanations are not exhaustive. They take up only those senses or applications of each term that the text is actually concerned with, and do not attempt general expositions of them. For further information on any item in the glossary, the student should consult the index to locate further discussion in the text of this book. For more general and exhaustive information, the student should consult a good technical dictionary, an engineering handbook, or an engineering or physics text.

ACCELEROMETER: An instrument that measures one or more components of the accelerations of a vehicle.

ACTIVE MATERIAL: Fissionable material, such as Pu 239, U 235, or the Thorium-derived uranium isotope U 233, which is capable of supporting a chain reaction. In the military field of atomic energy, the term refers to the nuclear components of atomic weapons exclusive of the natural uranium parts.

AFC: An abbreviation for automatic frequency control. A circuit that maintains accurate frequency control.

AGC: An abbreviation for automatic gain control. A circuit arrangement that automatically maintains the output amplitude (sound level in audio receivers) essentially constant, despite variations in input signal strength.

AIR BURST: The explosion of a nuclear weapon at such a height that the expanding ball of fire does not touch the earth's surface when the luminosity is a maximum (in the second pulse). A typical air burst is one for which the height of burst is such as may be expected to cause maximum blast destruction on an average target. Fission products in a high or moderately high air burst will be widely dispersed. On the other hand, if the burst occurs nearer the earth's surface, the fission products may fuse with particles of the earth, much of which will fall to the ground at points close to the explosion. This dirt and other debris may be a radiation hazard. (See also "Surface Burst.")

ALTIMETER: A device to measure altitude. In missiles, it may be of the barometric pressure or electromagnetic radiation types.

AMPLIDYNE: A dynamoelectric power amplifier having a construction like that of a generator, but utilizing special windings in such a way that amplification ratios as high as 10,000 to 1 may be obtained.

AMPLIFIER: A device for increasing the magnitude of a quantity. Used in radio, electrical, pneumatic, audio, and hydraulic systems.

ATOMIC (NUCLEAR) ENERGY: Energy released when a neutron splits an atom's nucleus into smaller parts (fission) or when two nuclei are joined together under millions of degrees of heat (fusion). "Atomic energy" is a popular misnomer; it is more correctly called "nuclear energy."

ATTITUDE: The position of an aircraft or missile as determined by the inclination of its axes to some frame of reference. If not otherwise specified, this frame of reference is fixed with respect to the earth.

AUDIO FREQUENCY: A frequency which can be detected as sound by the human ear. The audio frequency range is normally understood to extend from 20 to 20,000 cycles per second.

AUTOSYN: A Bendix-Marine trade name for a synchro, derived from the words AUTOmatically SYNchronous. See "synchro."

BANDWIDTH: In electronics, the number of cycles, kilocycles, or megacycles expressing the difference between the lowest and highest frequencies of a portion of the frequency spectrum; for example, a TV or radio station channel assignment.

BARO: A pressure-sensitive device (essentially a pressure altimeter) used in some weapons to actuate circuits. The term is a contraction of "barometric switch," sometimes referred to as "baroswitch."

BASE SURGE: A cloud which rolls outward from the bottom of the column produced by a subsurface explosion. For underwater bursts the surge is in effect a cloud of liquid (water) droplets with the property of flowing almost as if it were a homogeneous fluid. For subsurface land bursts the surge is made up of small solid particles but it still behaves like a fluid. A soft earth medium favors base surge formation in an underground burst.

CANARD: A type of airframe having the stabilizing and control surfaces forward of the main supporting surfaces.

CARRIER: In electronics, the carrier is the basic RF wave upon which other signals are superimposed to transmit information.

CIRCULAR ERROR PROBABILITY (CEP): The radius of a circle about the aiming point within which there is a 50 percent probability of hitting.

COAXIAL CABLE (OR LINE): A cable or line having coaxial conductors separated by a dielectric (insulator.) The dielectric may be either a solid or a gas. Coaxial cables are used as transmission lines for radio, radar, and television signals.

CONICAL SCANNING: A radar scanning system in which a point on the radar beam describes a circle, and the axis of the beam generates a cone.

CONTACT BURST: See surface burst.

CONTAMINATION (RADIOACTIVE): The deposit of radioactive material on the surface of structures, areas, personnel, or objects.

CRUICIFORM: A configuration in the form of a cross with legs 90° apart.

CRYSTAL-CONTROLLED OSCILLATOR: An oscillator whose frequency is controlled to a high degree of accuracy by the use of a quartz crystal. This frequency is dependent on the physical dimensions of the crystal, especially its thickness.

CRYSTAL MIXER: A device using certain properties of a crystal (germanium, silicon) to mix two frequencies.

DECONTAMINATION: The process of removal of contaminating radioactive material from an object, structure, or an area. The problem of decontamination consists essentially of reduction of the level of radioactivity, and thus reduction of the hazard it imposes, to a reasonably safe limit.

DETECTOR: In electronics, the receiver stage in which demodulation takes place.

DISCRIMINATOR: In electronics, a stage that converts frequency-modulated RF signals into audio-frequency signals.

DOUBLER: In electronics, a frequency multiplier circuit that doubles the input frequency.

DUPLEXER: (sometimes referred to as a TR box.) This is a switch, or tube, which permits the use of a single antenna on a radar for both transmitting and receiving. The function of the duplexer is to prevent the absorption of transmitter energy into the receiver system, thereby protecting the receiver from damage, and also to prevent the transmitter circuits from absorbing any appreciable fraction of the reflected echo signal.

DYNAMOTOR: A combination electric motor and generator, often used to convert low-voltage d-c to high-voltage d-c.

ELECTRONICS: The broad field pertaining to the conduction of electricity through vacuum, gases, or semi-conductors, and circuits associated therewith.

ENVELOPE: In electronics, (1) the glass or metal tube housing of a vacuum tube; (2) a curve drawn to pass through the peaks of a graph showing the waveform of a modulated radio-frequency carrier signal.

EPILATION: Falling out of the hair.

FEEDBACK: The electrical or acoustical return of part of the output signal of a device or electric circuit, to an earlier stage of the same device or circuit.

FIDELITY (or accuracy): The degree with which a system or portion of a system accurately reproduces at its output the essential characteristics of the signal that is impressed on its input.

FILTER: In electronics, a device which blocks certain frequencies and allows certain other frequencies to pass through. Filters are classified according to usage as low pass, high pass, band pass, and band elimination.

FIREBALL (or ball of fire): The luminous sphere of hot gases which forms a few milliseconds after a nuclear explosion and immediately starts to expand and cool. The exterior of the fireball is initially sharply defined by the luminous shock front (in air) and later by the limits of the hot gases themselves.

FISSION PRODUCTS: The substances produced as a result of the fissioning of the nuclear material of atomic weapons. The fission of U-235, for example, yields more than 60 direct products, sometimes called "fission fragments," which are formed by the actual splitting of nuclei. The distinction between fission products and fission fragments is that the latter are direct products of fission. The fission fragments, being radioactive, immediately begin to decay, forming additional (daughter) products with a resulting complex mixture of fission products (over 200 nuclides).

GATE: In radar or control terminology, a circuit that permits another circuit to receive input signals only during a desired time interval.

GRID BIAS: Refers to the d-c voltage on the control grid of an electron tube (with respect to the cathode). A small variation in grid bias can control a larger amount of current flow through the electron tube.

GUIDED MISSILE: An unmanned vehicle moving about the earth's surface, whose trajectory or flight path is capable of being altered by a mechanism within the vehicle.

GYRO, DIRECTIONAL: A gyroscopic instrument for indicating direction, containing a free gyroscope which holds its position in azimuth and thus indicates angular deviation from course.

GYROSCOPE, FREE: A gyroscope mounted in two or more gimbal rings so that its spin axis is free to maintain a fixed orientation in space.

GYROSCOPE, RATE: A gyroscope with a single gimbal mounting, such that rotation about an axis perpendicular to the axis of the gimbal and to the axis of the gyro produces a precessional torque proportional to the rate of rotation.

HARMONIC: A component having a frequency which is an integral multiple of the fundamental frequency. For example, a component, the frequency of which is three times the fundamental frequency, is called the third harmonic.

HOT SPOTS: Regions in a contaminated area in which the level of radioactive contamination is considerably higher than in neighboring regions.

HUNTING: A condition of instability resulting from overcorrection of a control device and resultant fluctuations in the quantity intended to be kept constant.

HYDROGEN BOMB (or weapon): A term sometimes applied to nuclear weapons in which part of the explosive energy is obtained from nuclear fusion (or thermonuclear) reactions.

HYGROSCOPIC: Descriptive of a material which readily absorbs and retains moisture.

INDUCED RADIOACTIVITY: Radioactivity resulting from certain nuclear reactions in which exposure to radiation results in the production of unstable nuclei. Many materials near a nuclear explosion enter into this type of reaction, notably as a result of neutron bombardment.

INDUCTANCE: The property of an electrical circuit which tends to oppose any change of current in the circuit. The symbol for inductance is "L," and the unit of measure is the "henry."

INTEGRATING CIRCUIT: A circuit whose output voltage is proportional to the product of the instantaneous applied input voltages and their duration. Some integrating circuits are made to give an output proportional to input frequency and amplitude.

INTEGRATOR: A device which in effect adds up all the instantaneous values of a variable quantity over a given period of time.

INTERMEDIATE FREQUENCY (IF): The IF is that frequency selected from the result of mixing an incoming (to a receiver section) signal with that of the local oscillator in order to achieve a frequency more suitable for amplification (than the incoming signal), yet carry the same basic information.

KLYSTRON: A vacuum tube in which high frequency oscillations are generated by the bunching of electrons. Used as the local oscillator in radar receivers.

LEVELING CIRCUIT: A filter circuit used to level out fluctuations of a bias voltage.

LIMITER: In electronics, a circuit that limits the maximum positive or negative values of a waveform to some predetermined amount. It is used in frequency-modulated systems to eliminate unwanted variations of amplitude in received waves.

MAGNETRON: A high vacuum tube in which an external magnetic field is used to control the current flow. Used to generate microwaves (radar frequencies) with high output power.

MICROSYN: A name applied to a small type of synchro whose chief merit is that there are no electrical connections to the rotor. It can be used as an inductive potentiometer.

MICROWAVES: Extremely short radio waves that are not more than a few centimeters in wavelength.

MIXER: In electronics, a stage in which two quantities are combined to obtain a third quantity. The third quantity contains the intelligence of the original inputs. Those quantities not further desired can then be filtered out.

MODULATION: The process of varying the amplitude, frequency, or phase of a carrier wave, with time, to transmit information.

MODULATION, AMPLITUDE (AM): A method of modulating a radio-frequency (RF) carrier by causing the amplitude of the carrier to vary in accordance with the superimposed signal.

MODULATION, FREQUENCY (FM): A method of modulating a radio-frequency (RF) carrier by causing the frequency of the carrier to vary in accordance with the superimposed signal.

MODULATION, PHASE (PM): A method of modulating a radio-frequency (RF) carrier by causing the phase of the carrier to shift in accordance with the superimposed signal.

MULTIPLEX: Denotes the simultaneous transmission of several functions over one link without loss of detail of each function, such as amplitude, frequency, phase, or wave shape.

MULTIPLEXER: A device by which two or more signals may be transmitted on the same carrier wave.

MULTIVIBRATOR: A vacuum tube oscillator circuit whose output is essentially a square wave. A practical application is its use as a sweep generator in TV or radar circuitry.

NUCLEAR WEAPON (or bomb): A general name given to any weapon in which the explosion results from the energy released by reactions involving atomic nuclei (either fission or fusion, or both). Thus, the A (or atomic) bomb, the H (or hydrogen) bomb, and the TN (or thermonuclear) bomb are all nuclear weapons. It would be equally correct to call them atomic weapons since

it is the energy of the atomic nuclei that is involved in each case. However, it has become more or less customary, although it is not strictly accurate, to refer to weapons in which all the energy results from fission as A (or atomic) bombs. In order to make a distinction, those weapons in which part, at least, of the energy results from thermonuclear (fusion) reactions among the isotopes of hydrogen have been called H, TN, or hydrogen bombs.

NUCLIDE: A general term referring to all nuclear species—both stable (about 270) and unstable (about 500)—of the chemical elements, as distinguished from the two or more nuclear species of a single chemical element which are called "isotopes."

NUTATION: A motion similar to the nodding of a slowly spinning top.

ORALLOY: A contraction for the term "Oak Ridge alloy," and used to identify the material first refined at Oak Ridge—U-235.

OSCILLATOR: In electronics, the stage designed to set up and maintain oscillations of a frequency determined by the electrical constants of the stage. In general, the stage makes use of a vacuum tube.

OVERPRESSURE: The transient pressure, usually expressed in pounds per square inch, exceeding existing atmospheric pressure, manifested in the blast wave from an explosion. During some period of the passage of the wave past a point, the overpressure will be negative.

PETECHIAE: A condition characterized by small spots on the skin. It is caused by the escape of blood into the tissues.

PHASE SHIFTER: A circuit or stage that changes the phase of the input signal. This phase shifting may be used to develop a fixed or varying output.

PHOTOMULTIPLIER TUBE: A light-sensitive vacuum tube containing multiple anodes that provide a cumulative increase in output each time the light beam strikes an anode. Used in radar mapmatching guidance systems.

PULSE REPETITION RATE (PRR): also, Pulse Recurrent Rate or Pulse Repetition Frequency (PRF): These terms refer to the repetition rate or frequency of pulses transmitted by radar. Most radars use the pulse-modulation method of transmitting RF (radio-frequency) energy. PRR is a characteristic which describes the number of pulses transmitted per unit of time.

PURPURA: Medical term for a symptom characterized by the appearance of purple patches on the skin and mucous membranes, due to hemorrhage in the fatty tissues beneath the skin.

QUANTUM: A discrete quantity of radiative energy equal to the product of its frequency and Plank's constant. The equation is E=hv.

QUANTUM THEORY: The concept that energy is radiated intermittently in units of definite magnitude called QUANTA.

R-C CIRCUIT: An abbreviation for resistance capacitance circuit. It is one of the methods used to couple two electronic circuits together. Some of the characteristics of R-C coupling are wide frequency response and lower cost and size than that of transformer or other inductive coupling systems.

RADIATION: A method of transmission of energy, specifically: (1) Any electromagnetic wave (quantum); (2) Any moving electron or nuclear particle, charged or uncharged, emitted by a radioactive substance.

RADIO FREQUENCY (RF): Any frequency of electrical energy capable of propagation into space. Radio frequencies normally are much higher than sound-wave frequencies.

RADIONUCLIDE: An unstable nuclide.

REACTION, CHEMICAL: Involves a change in molecular structure (chemical properties change but atoms remain unchanged).

REACTION, NUCLEAR: A change to the atomic structure of the element involved so that the products are different elements and energy.

REGENERATIVE: Feeding back. A regeneratively cooled rocket motor is one in which one of the propellants is used to cool the motor by passing through a jacket prior to combustion.

RELAY: In electronics, there are two related meanings for the term relay. First, the relay may be an electromechanical device which when operated by an electrical signal will cause contacts to make or break, thereby controlling one or more other electrical circuits. The solenoid is the basic mechanism of this type of relay. Second, the relay may be an electronic network to receive and transmit information. There is usually an amplification stage in the relay process.

SATURABLE REACTOR: In electronics, an inductive device (a principle of magnetism) which makes use of its core's inductive saturation point to control (and perhaps amplify) current flow.

SELSYN: A General Electric trade name for a synchro, derived from SELF-SYNchronous. See "Synchro."

SERVO-LINK: A power amplifier, usually mechanical, by which signals at a low power level are made to operate control surfaces requiring relatively large power inputs; e.g., a relay and a motor-driven actuator.

SERVO SYSTEM: A closed-cycle automatic-control system so designed that the output

element or output quantity follows as closely as desired the input to the system. The output is caused to follow the input by the action of the servo controller upon the output element in such a way as to cause the instantaneous error, or difference, between output and input to approach zero. All servo systems are dynamic systems containing at least one feedback loop which provides an input signal proportional to the deviation of the actual output from the desired output. This property distinguishes servo systems from ordinary automatic control systems. In general, servo mechanisms exhibit the following properties: (1) include power amplification; (2) are "error sensitive" in operation; and (3) are capable of following rapid variations of input.

SERVOMOTOR: A special electric, hydraulic, or other type of motor that can be used as a mechanical relay in control apparatus to convert a small movement into one of greater amplitude or greater force.

SIGNAL: Any waveform or variation thereof, with time, serving to convey the desired intelligence in communication.

SPECIAL WEAPON: Within the Department of Defense this term is synonymous with "Nuclear Weapon."

SQUIB: A small pyrotechnic device which may be used to fire the igniter in a missile booster rocket, or for some similar purpose. Not to be confused with a detonator which explodes.

STRAIGHT-THROUGH RF AMPLIFIER: An amplifier whose output frequency is the same as its input frequency.

SUPERHETERODYNE: The term "heterodyne" refers to two frequencies mixed (or beat) together. The frequency mixing produces two beat frequencies which are the sum of and difference between the two original frequencies. A superheterodyne receiver is one in which the incoming signal is mixed with a locally generated signal to produce a predetermined intermediate frequency. The purpose of the superheterodyne receiver is to achieve better amplification over a wide T band of incoming signal frequencies than could be easily achieved with an RF amplifier.

SUPERREGENERATIVE SET: A type of high frequency (VHF, UHF) receiver which is ultra sensitive. Advantages are extreme sensitivity, simplicity, and reliability. Disadvantages are broadness of tuning (poor selectivity), and reradiation that can cause interference in other receiving equipment.

SURFACE BURST, NUCLEAR WEAPON: The explosion of a nuclear weapon at a height where the fireball at maximum luminosity (in the second thermal pulse) touches the ground (or water). An explosion in which the bomb is detonated with its point of origin on the surface is called a "contact burst" or a "true surface burst." The energy of a surface burst will cause both air blast and ground (or water) shock, in varying proportions, depending upon the height of burst above the surface. (Although the four types of bursts have been more or less distinctively defined for the purposes of this orientation, there is actually no clear line of demarcation between them; see also Air burst, Underwater burst, and Underground burst.)

SYNCHRO: The universal term applied to any of the various synchronous devices as the Selsyn, Autosyn, motor torque generator, mag-slip, and Siemans. Theoretically a synchro device is treated as a salient-pole, bipolar, alternating-current excited synchronous machine. The standard signal and control synchro has a two-pole, single-phase, variable-voltage stator. The transmitter of the synchro, whose rotor is otherwise linked with mechanical equipment, is also called a generator, synchro generator, or a Selsyn generator. The indicator, also called a motor, synchro motor, or Selsyn motor, has a rotor that is free to rotate, and is damped to prevent excessive oscillation before coming into correspondence with the rotor of the transmitter.

THERMONUCLEAR (TN): An adjective referring to the process(es) in which very high temperatures are used to bring about the fusion of light nuclei, such as those of the hydrogen isotopes, deuterium and tritium, with the accompanying liberation of energy. A thermonuclear bomb is a weapon in which part of the explosion energy results from the thermonuclear reactions. The high temperatures required are obtained by means of a fission explosion.

TONE GENERATOR: An electronic or mechanical device whose function it is to generate a frequency in the audio range.

TRANSDUCER: A device to transmit energy from one medium (or system) to a different medium (or system). A loudspeaker and a phonograph pick-up are two examples of transducers; the former changes electrical energy into acoustical energy, and the latter changes mechanical energy into electrical energy.

TRANSMUTATION: Any process in which a nuclide is transformed into a different nuclide, or more specifically, transformed into a different element by a nuclear reaction.

TUBALLOY: A colloquial term which refers to natural uranium or to metal which is composed almost entirely of U-238. It is a

515354 O - 59 - 19

contraction of "Tube Alloy," a code name used originally to mean naturally occurring uranium which is not easily fissioned.

UMBILICAL CORD: A cable fitted with a quick disconnect plug at the missile end, through which missile equipment is controlled, monitored, and tested while the missile is still attached to its launcher.

UNDERGROUND BURST, NUCLEAR WEAPON: The explosion of a nuclear weapon in which the origin is beneath the surface of the earth. Most of the energy of the underground burst appears as ground shock, but a certain proportion (varying with the depth of explosion) may escape and produce air blast. (See also "surface burst.")

UNDERWATER BURST, NUCLEAR WEAPON: One in which the origin of the explosion is beneath the surface of a body of water. Most of the energy of the underwater burst appears as underwater shock, but a certain proportion (dependent on the depth) may escape and produce air blast. (See also "surface burst.")

VIDEO: The term is applied to the frequency band of circuits by which visual signals are transmitted. The term "video" is also used when speaking of a very wide band of frequencies, including and exceeding the audio band of frequencies.

WAVEGUIDE: A guide, consisting of either a metal tube or dielectric (insulator) cylinder, capable of propagating electromagnetic waves through its interior. The dimensions of such a guide are determined by the frequency of the wave to be propagated. Metal guides may be evacuated, air filled, or gas filled, and are generally rectangular or circular in cross-section. Dielectric guides consist of solid or hollow cylinders of dielectric material.

YIELD: The energy released in a nuclear explosion, usually measured by the estimated equivalent amount of TNT required to produce the same energy release.

INDEX

U. S. GOVERNMENT PRINTING OFFICE : 1959 O - 515354